DESIGN OF AN AUTONOMOUS TELEOPERATED CARGO TRANSPORTING VEHICLE FOR LUNAR BASE OPERATIONS

Submitted to:

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MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM
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November 15, 1989

James A. Aliberti
Manager of Research Programs
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Dear Mr. Aliberti:

Attached is our final report entitled "Design of an Autonomous, Teleoperated Cargo Transporting Vehicle for Lunar Base Operations". This report contains a description of the cargo transporting vehicle and its operation, detailed analyses of several subsystems, a comparison to the Lunar Roving Vehicle, and our recommendations for future design and development of the vehicle.

The team is looking forward to seeing you at the final design presentation. The presentation is scheduled for Tuesday, December 5, 1989, at 10:00 a.m. in the Engineering Teaching Center II, Room 4.110, on the campus of The University of Texas at Austin. A catered luncheon will follow the presentation at noon.

Sincerely,

James Holt, Team Leader

Tom Lao

Tom Lao

Nkoy Monali

ACKNOWLEDGEMENTS

The team members would like to thank the National Aeronautics and Space Administration (NASA), the Universities Space Research Association (USRA), and Mr. James A. Aliberti from the Kennedy Space Center for sponsoring this project.

Special thanks goes to Dr. Kris Wood, our faculty advisor, for his technical and editorial assistance, and for showing confidence in the team's capabilities throughout the project.

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The team would also like to thank Mr. Richard B. Connell, Teaching Assistant, and Mr. Bert Herigstad, Design Projects Administration Assistant, for their technical and administrative assistance throughout the project.

ABSTRACT

DESIGN OF AN AUTONOMOUS, TELEOPERATED CARGO TRANSPORTING VEHICLE FOR LUNAR BASE OPERATIONS

At the turn of the century, the National Aeronautics and Space Administration (NASA) plans to begin construction of a lunar base. The base will likely consist of developed areas (i.e. habitation, laboratory, landing and launching sites, power plant) separated from each other due to safety considerations. The team has designed the Self-Repositioning Track Vehicle (SRTV) to transport cargo between these base facilities. The SRTV operates by using two robotic arms to raise and position segments of track upon which the vehicle travels. The SRTV utilizes the Semiautonomous Mobility (SAM) method of teleoperation, actuator-controlled interlocking track sections, two robotic arms each with five degrees of freedom, and these materials: titanium for structural members, aluminum for shell members, with the possibility of using light-weight, high-strength composites.

KEY WORDS: LUNAR, TRANSPORTATION, TELEOPERATION, ROBOTICS

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INTRODUCTION

The United States National Aeronautics and Space Administration (NASA) is a government agency established in 1958 to coordinate and conduct space research and exploration. NASA has contracted the Universities Space Research Association (USRA) to establish a partnership between NASA engineers and university students and faculty for the education in, and development of space science and technology. The USRA is a private consortium organized in 1969 by the National Academy of Sciences to promote interaction between universities and corporate research institutions.

The NASA/USRA Advanced Design Program integrates selected NASA space/aeronautics design projects into universities' senior design courses. The objectives of the Advanced Design Program are to enhance student's design experiences and to provide NASA with new design ideas from bright young students. The team has designed an autonomous, teleoperated cargo transporting vehicle for NASA's proposed lunar base. The remainder of this report describes the alternative systems available, the design solution, and recommendations for this design.

BACKGROUND

NASA and its space system contractors and consultants are designing a manned lunar base with construction set to begin early in the next century. The reasons for establishing a lunar base involve science, resource, and technology development considerations. The primary commercial benefits of a lunar base lie in the extraction of oxygen from the lunar soil. Lunar oxygen (LUNOX) is an important element for maintenance of a space station, support of a lunar base, and further interplanetary missions as it will be used in life support, propulsion, and water production.

One concept of a lunar base has it comprised of separated facilities such that the habitation and laboratory center is safely away from the landing/launching sites and the power plant (see Figure 1). Storage garages, maintenance garages, and other facilities are located within the base with the distance separating each facility being dictated by safety factors. For example, landing and launching sites are separated from habitation facilities to protect the astronauts and equipment from errant space craft landings or launches, and thrown dust by the engine blast.

The team has designed an autonomous, teleoperated cargo transporting system connecting these separated facilities. The system will eliminate the need for manual cargo transportation and thus replace the leading cargo transporting candidate, the lunar roving vehicle (see Figure 2). A system that does not require manual cargo transportation is preferred because it reduces the likelihood of injury to the astronauts and frees them for more important tasks.

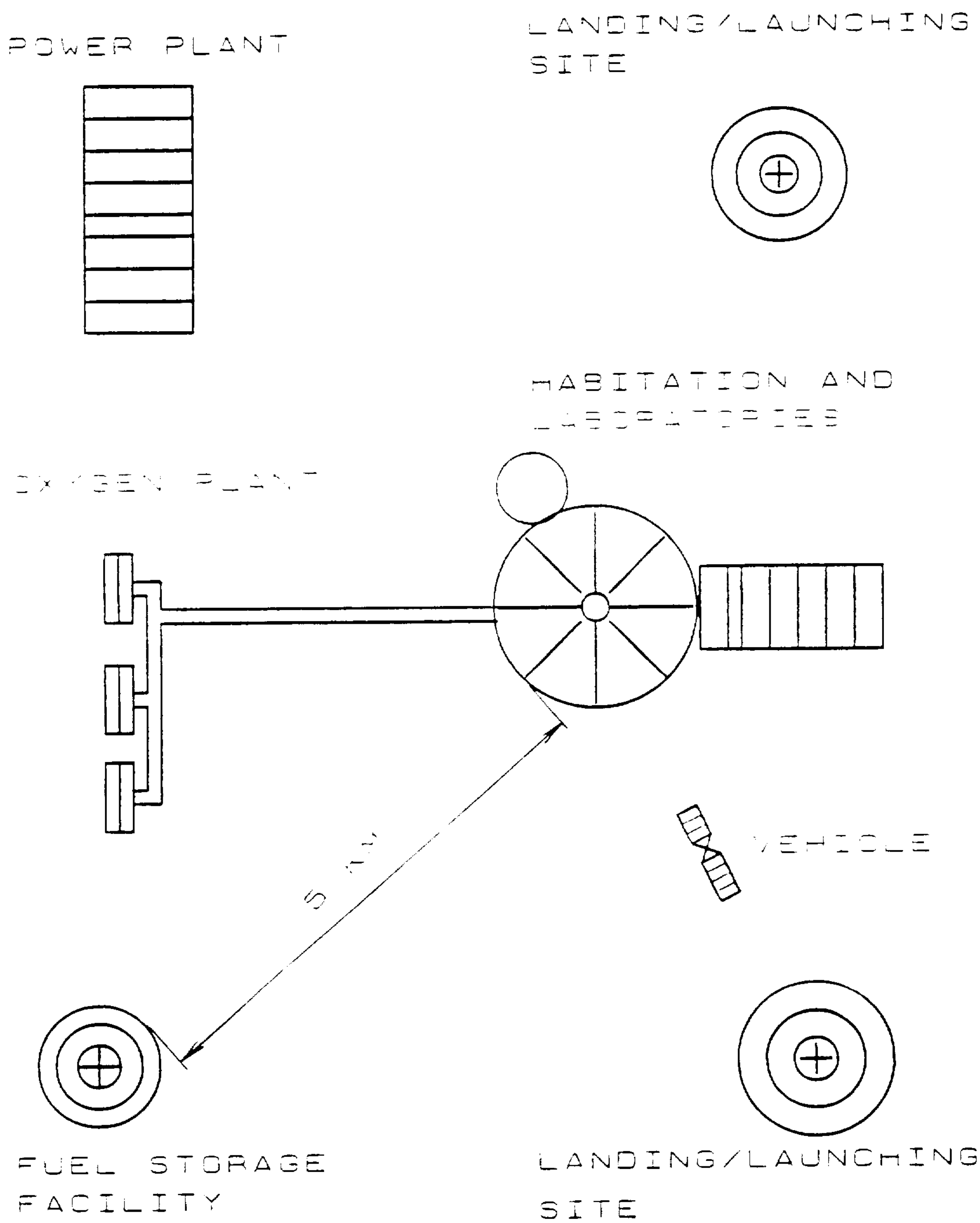
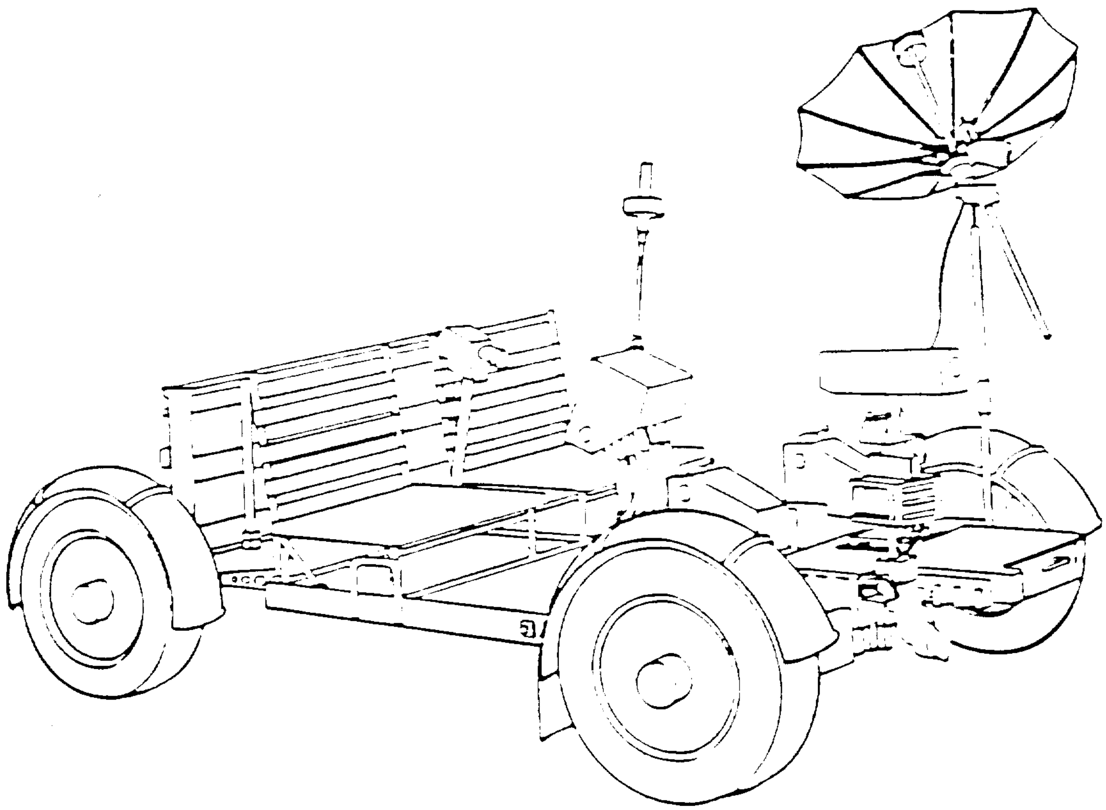


Figure 1. ONE CONCEPT OF A LUNAR BASE



NASA

Marshall Space Flight Center
Huntsville, Alabama

Figure 2 LUNAR ROVING VEHICLE

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PROJECT REQUIREMENTS

The team was asked to fulfill the following project requirements:

1. Design an unmanned, teleoperated cargo transporting system for NASA's proposed lunar base,
2. Compare and contrast the design team's system with the lunar roving vehicle, and
3. Construct a scaled demonstration model.

DESIGN CRITERIA

The team has adhered to the following design criteria for the lunar cargo transporting system:

1. Maximize personnel safety,
2. Minimize total weight,
3. Eliminate manpower in transporting cargo,
4. Minimize power consumption,
5. Minimize packing space for transporting to the moon,
6. Maximize ease of assembly, disassembly, and relocating on the lunar surface, and
7. Utilize electrical energy as the primary energy source.

SOLUTION METHODOLOGY

The team designed the autonomous, teleoperated cargo transporting vehicle using a five step process: investigation of resources, generation of alternate designs, selection of the best design, optimization of the best design, and construction of a scaled model.

The team investigated resources mainly from libraries, advisors, and NASA. Libraries provided computer searches, books, periodicals, and microfiche. Advisors informed the team of recent technology, further technical contacts, and design feasibility. NASA provided information through technical reports, information bulletins, and additional contacts. Past methods of lunar transportation and proposed methods of lunar and Mars transportation were also investigated.

The alternate designs were generated by altering or combining ideas for the system's type of operation (mode of transportation). For example, two types of operation are rail and suspended cable, both of which merit separate designs.

The team used a decision matrix to select the best design from the alternative designs. Designs were compared to each other, judged by a set of decision criteria, and all but the best design were eliminated.

In optimizing the design, the team designed for structural integrity, safety, minimal weight, minimal power consumption, and other design criteria. The design team conducted an analysis of the system's benefits and limitations, comparing them to those of the Lunar Roving Vehicle.

A scaled model was constructed to demonstrate the system's operation. The model is of the same scale with the models from other NASA/USRA Mechanical Engineering project teams at The

University of Texas at Austin to illustrate the interfacing between the four different project teams' designs.

Finally, the team had weekly discussions with the faculty advisor, Dr. Kris Wood, and the other student teams involved in the NASA/USRA lunar base projects at The University of Texas at Austin. These meetings provided guidance and ideas for the project.

During the investigation of resources, the team generated several alternative designs to accomplish the need of cargo transporting. The advantages and disadvantages of each design were listed and are discussed in the following section.

ALTERNATE DESIGNS

This section presents seven design alternatives for the unmanned cargo transport system. The emphasis during brainstorming was to include as many modes of transportation as possible. For example, someone wishing to transport cargo from New York City to Boston, Massachusetts would have a variety of modes of transportation available: automobile, bus, aircraft, railway, or ship, among others. Similarly, cargo transportation across the lunar surface could be accomplished via a number of modes of transportation. The seven alternate designs are grouped under three different modes of transportation as follows:

I. Autonomous, Teleoperated Cargo Transporting Vehicle

   A. Tank Tread Driven
   B. Wheeled
   C. Self-Repositioned Track

II. Overland Suspension System

   A. Self-Propelled
   B. Winch-Driven

III. Surface Rail System

   A. Wheeled
   B. Magnetically Levitated

For the remainder of this section, the cargo containers are described, the three modes of transportation are discussed, and the general operation, advantages, and disadvantages of each of the seven alternate designs are explained.

CARGO CONTAINERS

Cargo for the lunar base will be brought from the earth to the moon in one large, cylindrical cargo module (space station common module) measuring four and one half meters in diameter and thirteen and one half meters in length (see Figure 3). This large module will hold many smaller cargo containers and, following the removal of these containers, will be used as a habitation module.

Since the module is so large and massive when fully-loaded, it will not be transported to the base from the landing site in one trip. Rather, the design team's transport system will haul the smaller cargo containers separately to their destinations within the lunar base. Therefore, approximately ten to forty trips are necessary between sites for container volumes of 10 and 2 cubic meters, respectively.

AUTONOMOUS, TELEOPERATED CARGO TRANSPORTING VEHICLE

An autonomous, teleoperated cargo transporting vehicle is operated independently of any rail or guide. The "driver" operates the vehicle either from the lunar base or from the earth through teleoperation. If teleoperated from earth, a two-and-a-half second lag accompanies the signal, causing slower vehicle speeds because

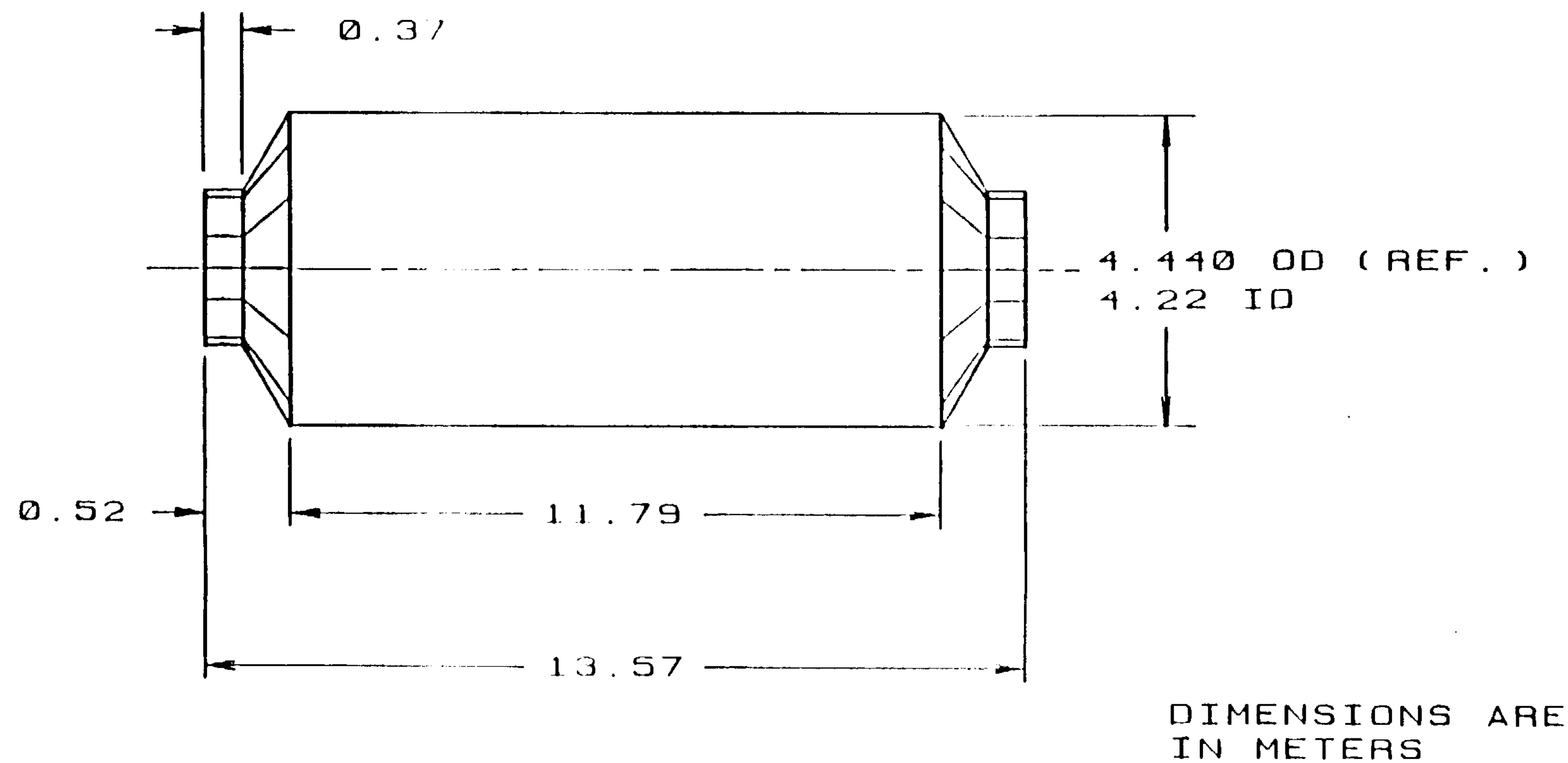

Figure 3: NASA COMMON MODULE SPECIFICATIONS

the operator does not have instantaneous control of the vehicle. Teleoperation allows the astronauts to concentrate on other tasks and, since astronauts are not needed to transport the cargo, the chances of an accident with injury are reduced. Three possible means of supporting and propelling this vehicle are through tank treads, wheels, and self-repositioning track.

Tank Tread-Driven Autonomous, Teleoperated Cargo Vehicle. The tank tread-driven cargo vehicle uses tank treads to advance the vehicle over the lunar terrain (see Figure 4). The tread is driven by an array of gears powered by an electric motor.

Advantages

1. Relocation of the system does not necessitate the disassembling and assembling of the system.

2. Rough surfaces can be traversed.

3. Teleoperation of the vehicle eliminates the manpower required for cargo transport.

4. The vehicle can be used for other purposes including exploration beyond the base.

Disadvantages

1. The abrasive dust wears moving parts, reducing the performance of the vehicle or requiring frequent maintenance.

2. Many moving parts increase the complexity of the design and increase the chances of mechanical failure.

3. The algorithm for teleoperation is complex.

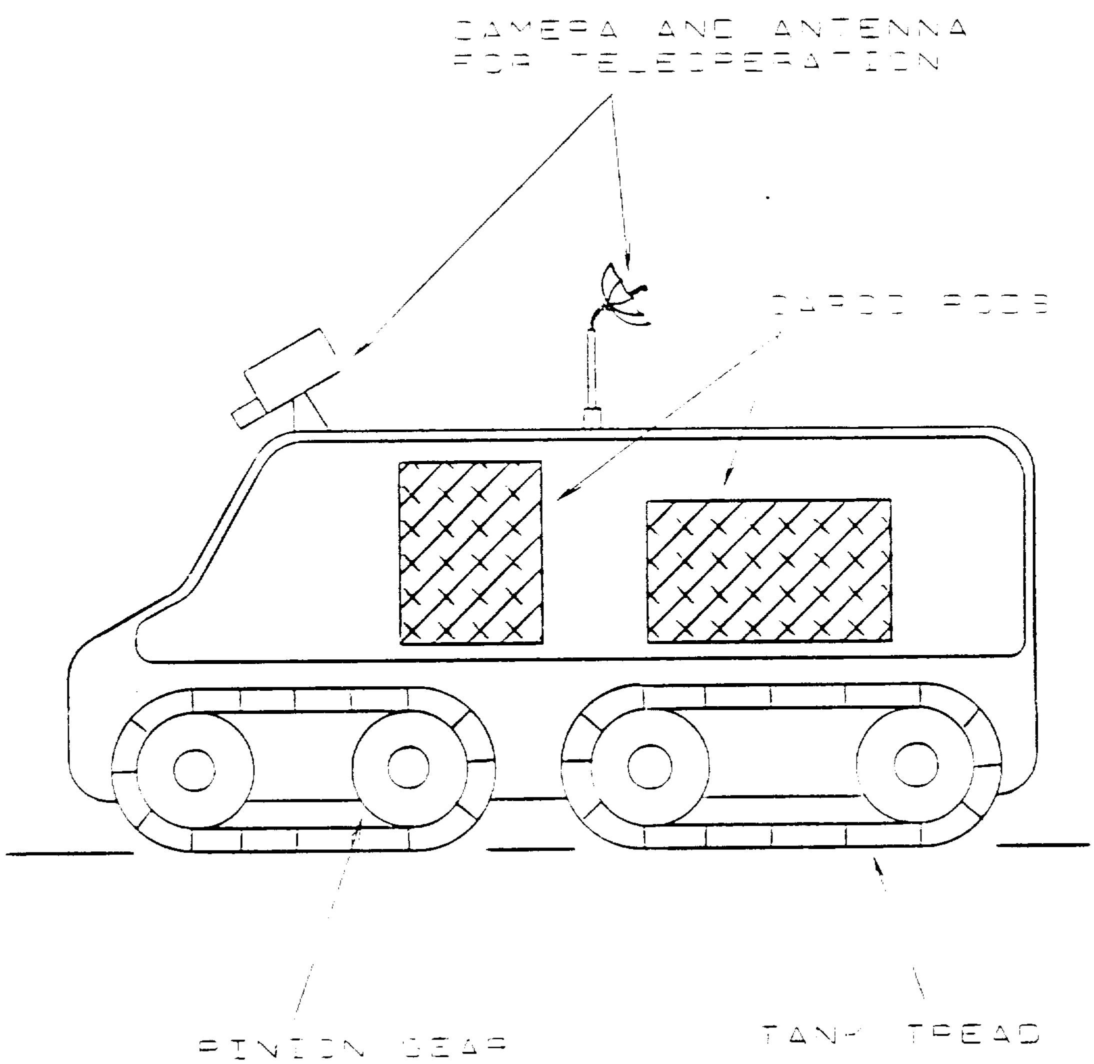

Figure 4 AUTONOMOUS TELEOPERATED CARGO VEHICLE USING TANK TREAD

4. Teleoperation from the earth would slow the vehicle response because the Earth-Moon distance causes a 2.5 second delay of signal travel.

Wheel-Driven Autonomous, Teleoperated Cargo Vehicle. The wheel-driven cargo vehicle has a flat storage bed which is supported and propelled with an array of wheels (see Figure 5). Stored electrical energy supplies power to a motor which drives the vehicle.

Advantages

1. Relocation of the system does not require disassembling and assembling the system.

2. Moderate terrain can be traversed.

3. Teleoperation of the system eliminates the manpower required for cargo transport.

4. The vehicle can be used for other purposes including exploration beyond the base.

Disadvantages

1. The abrasive dust wears moving parts, reducing the performance of the vehicle or requiring frequent maintenance.

2. The algorithm for teleoperation is complex.

3. Teleoperation from the earth would slow the vehicle response because the Earth-Moon distance causes a 2.5 second delay of signal travel.

Self-Repositioning Track System. The self-repositioning track system is an autonomous vehicle that picks up the track it rides over and places it in front of the vehicle. The rear robotic arm picks up the

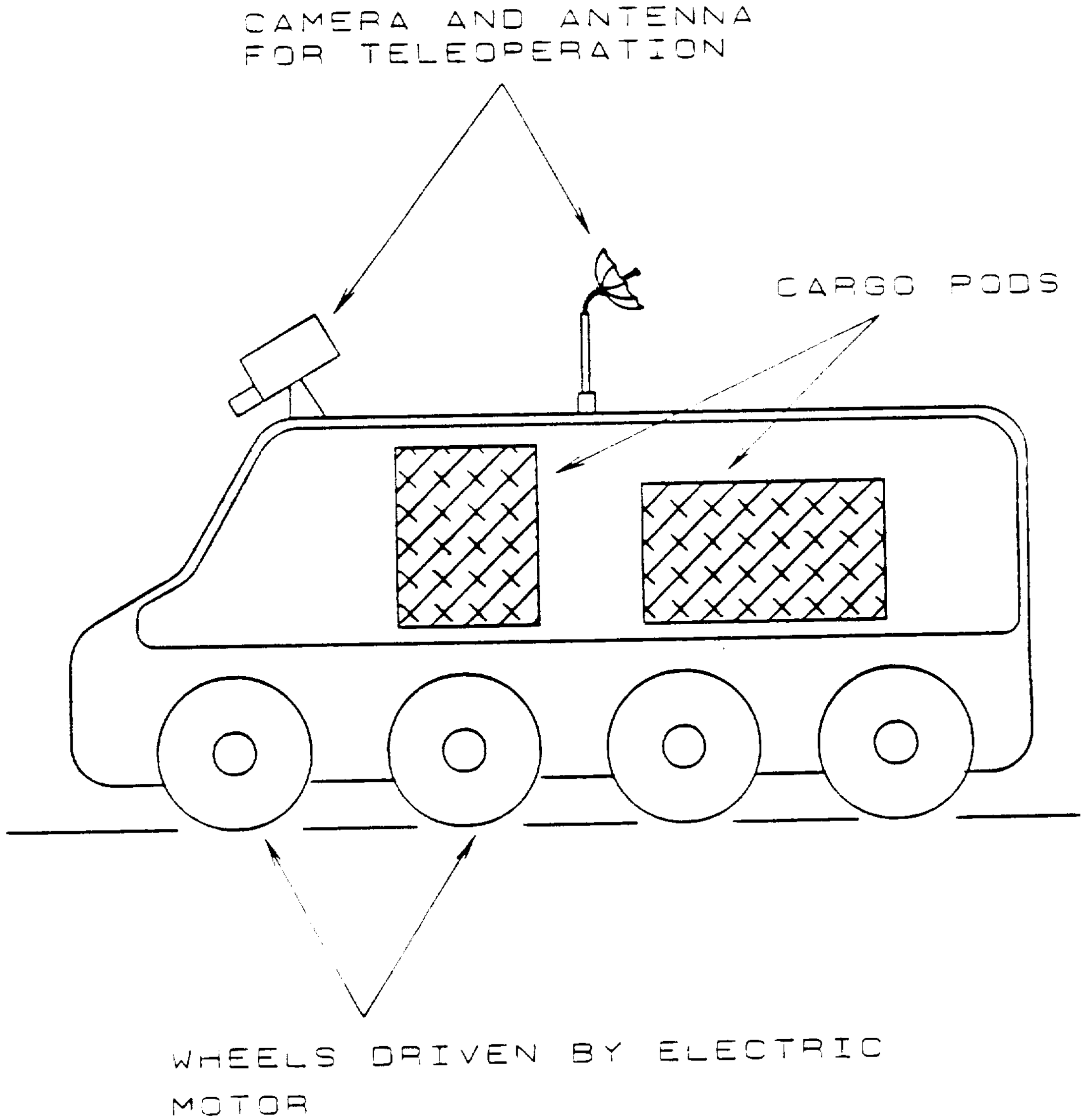

Figure 5 AUTONOMOUS TELEOPERATED CARGO VEHICLE USING WHEELS

track sections that the vehicle rides on and carries them to the roof. Once on the roof, the track sections are carried forward on a conveyor belt and lowered by the front robotic arm to the ground in front of the vehicle (see Figures 6 and 7).

Each track section has three subsections which are connected by hinges with self-locking mechanisms. Upon turning, a track section is moved on the track direction molder which forces an angle between the subsections. The three subsections are held at this angle by the self-locking mechanisms (see Figure 8).

The vehicle is supported and guided through the track by wheels. The power source which supplies electricity to the motors is stored electrical energy.

Advantages

1. Relocation of the system does not require disassembling and assembling the system.

2. The vehicle has a low rolling resistance during contact with the track.

3. Teleoperation of the system eliminates the manpower required for cargo transport.

4. The vehicle can be used for other purposes including exploration beyond the base.

Disadvantages

1. The system needs precise control of track position.

2. The need for precise control slows the system.

3. The system requires a flat surface for operation.

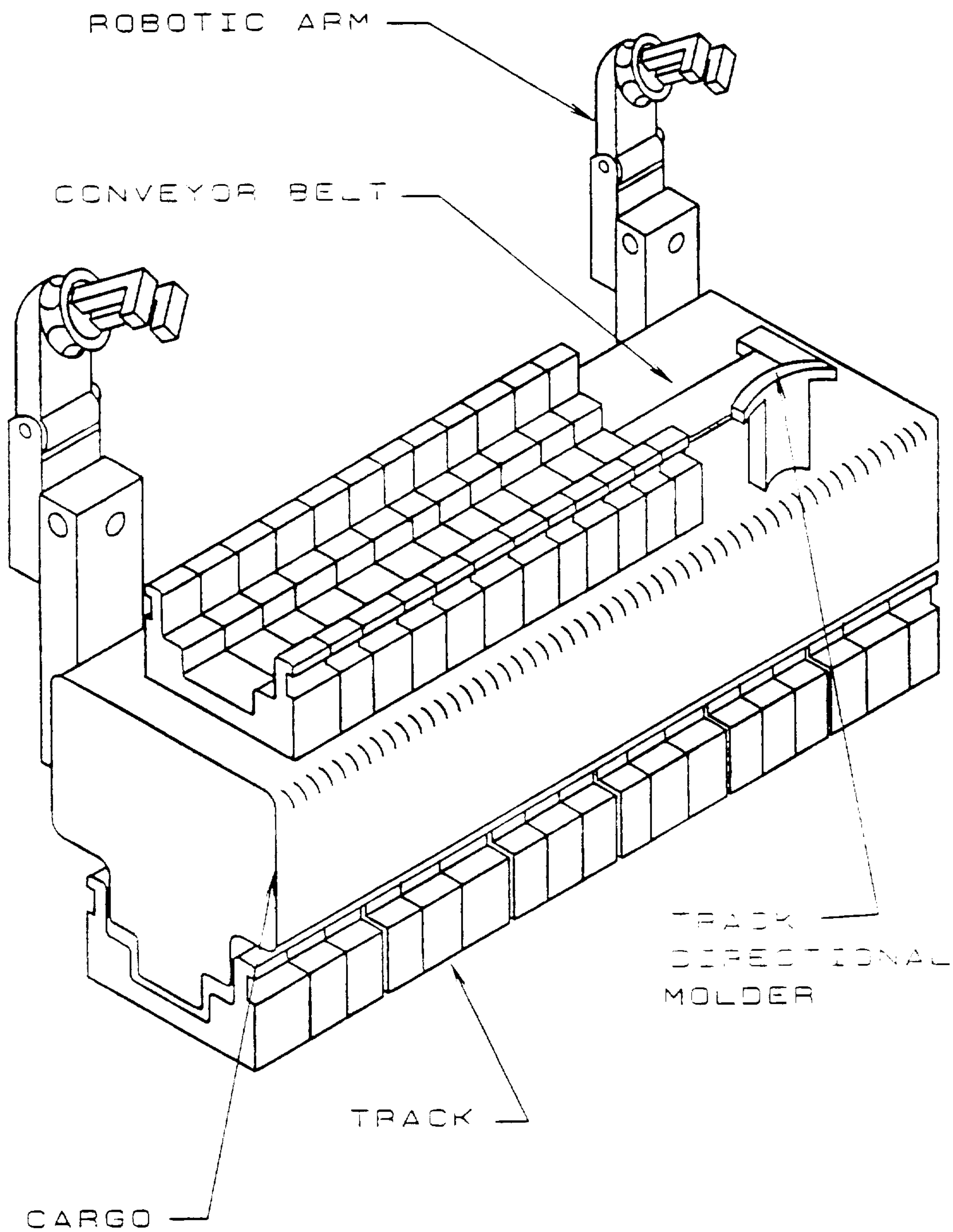

Figure 6. SELF-REPOSITIONING TRACK SYSTEM

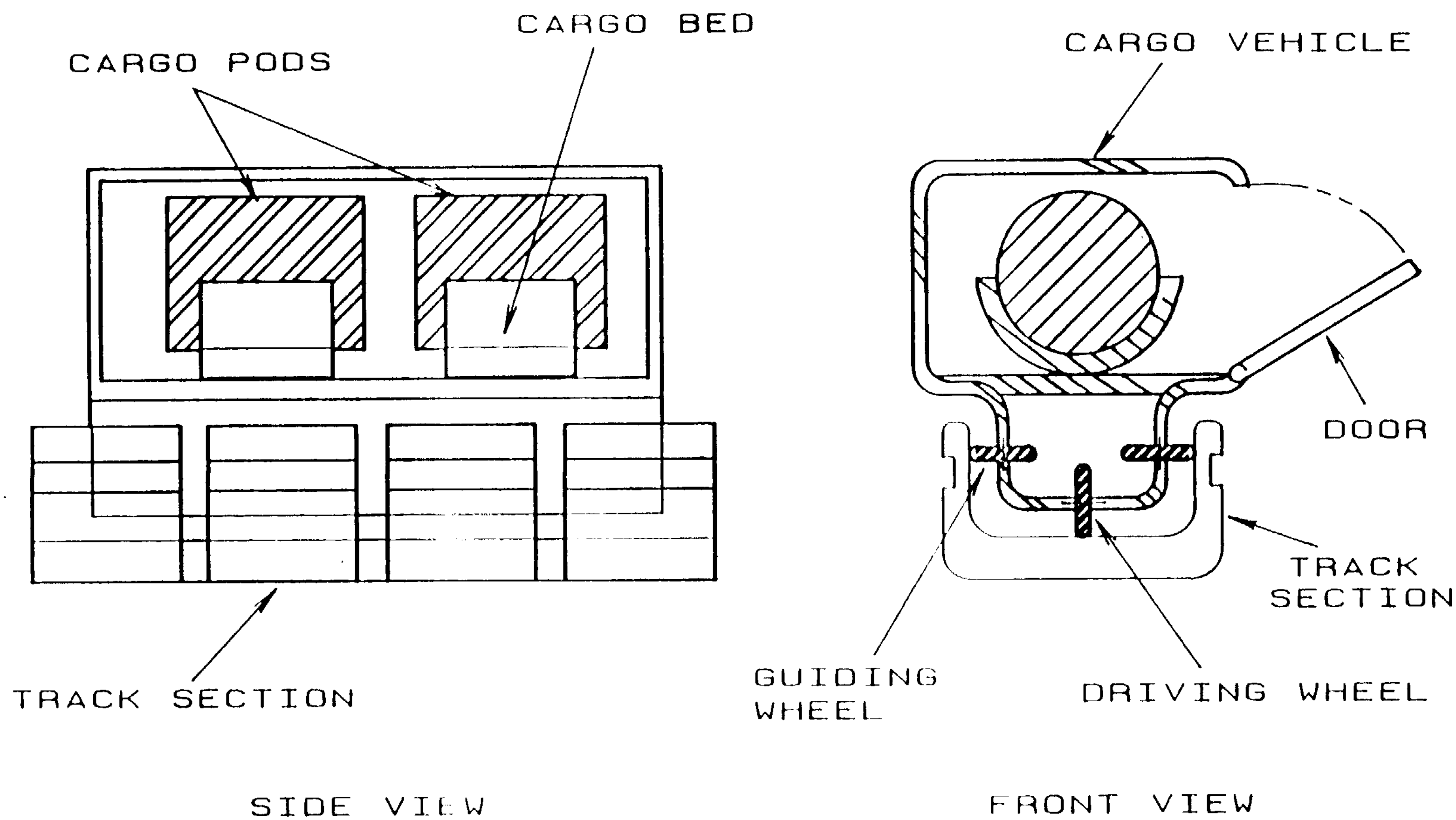

Figure 7: SIDE AND FRONT VIEWS OF THE SELF REPOSITIONING TRACK SYSTEM

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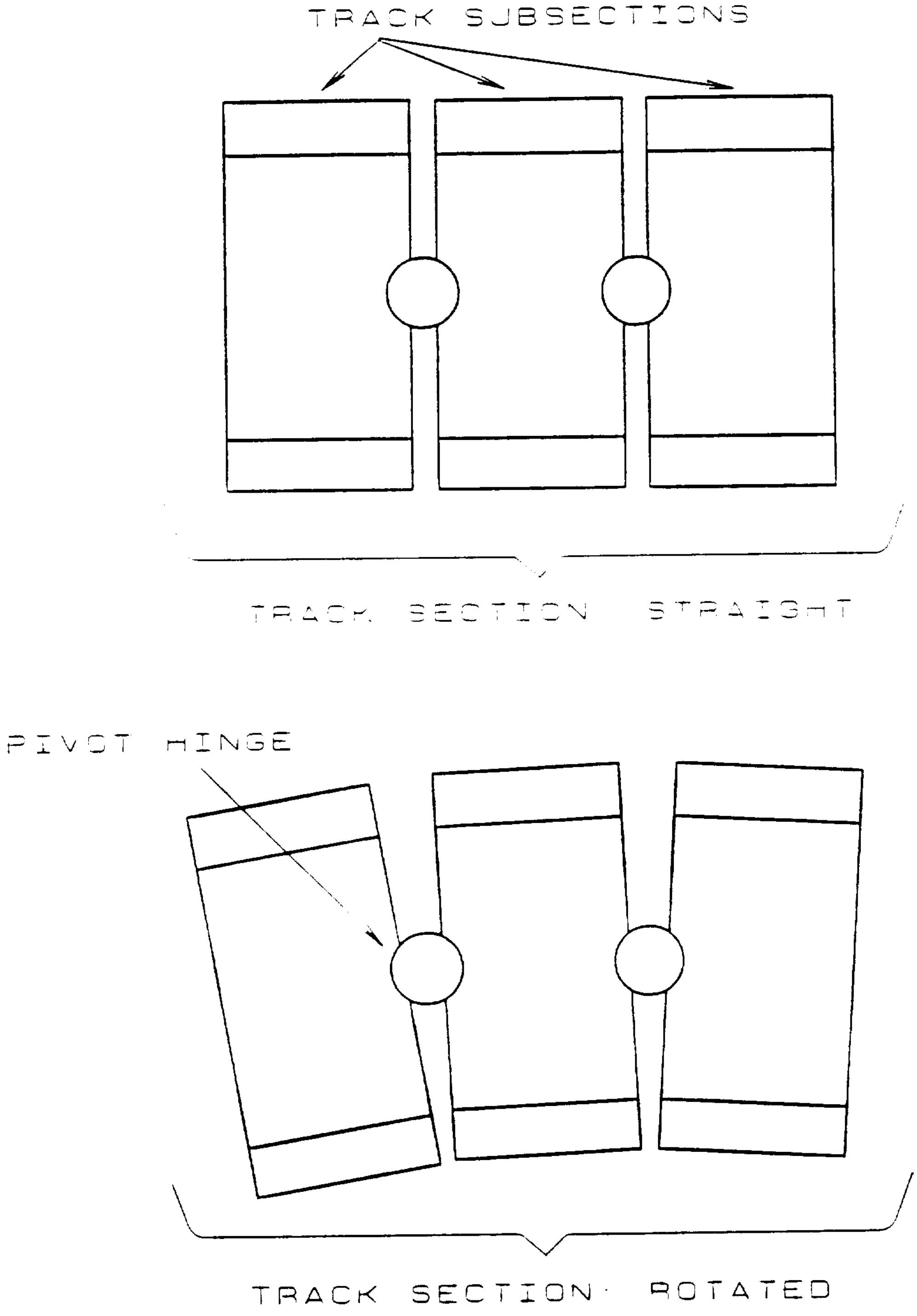

Figure 8 TOP VIEW OF STRAIGHT AND CURVED TRACK SUBSECTIONS

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4. Teleoperation from the earth would slow the vehicle response because the Earth-Moon distance causes a 2.5 second delay of signal travel.

5. The driving mechanisms for translational motion and for the positioning of the tracks is complex.

OVERLAND SUSPENSION SYSTEM

An overland suspension system carries the cargo above the lunar surface so as to avoid rough terrain and abrasive dust clouds. Since lunar dust is so abrasive, it presents a problem of wear as it works its way between moving parts.

Retractable posts are erected to support a rigid, but foldable track on which the cargo transporter will travel (see Figure 9). Retractable posts and tracks facilitate the relocation of the system. One possible way of retracting the system is by folding as illustrated in Figure 10. The suspended cargo holder is propelled in one of two ways, either self-propelled or pulled by a winch-driven cable.

Self-Propelled Overland Suspension System. The self-propelled version of the overland suspension system contains its own motor and energy storage devices (see Figure 11). Power is transmitted from the motor through gears and wheels that roll on the suspended rail to provide motion.

Advantages

1. The system avoids creating lunar dust clouds, which can enter between moving parts and promote wear.

2. The system can traverse rough terrain.

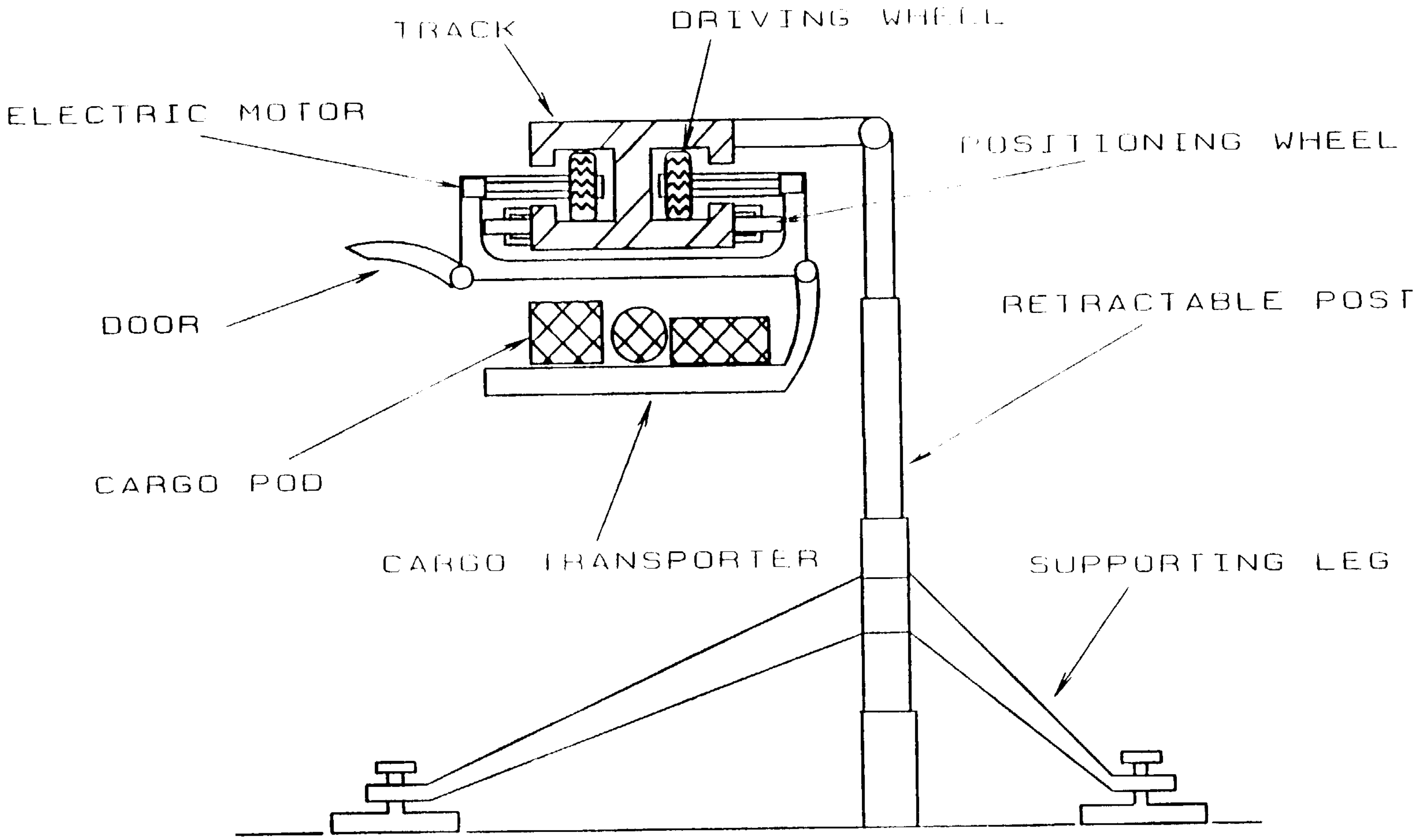

Figure 9. FRONT VIEW OF SELF-PROPELLED OVERLAND CARGO TRANSPORTER

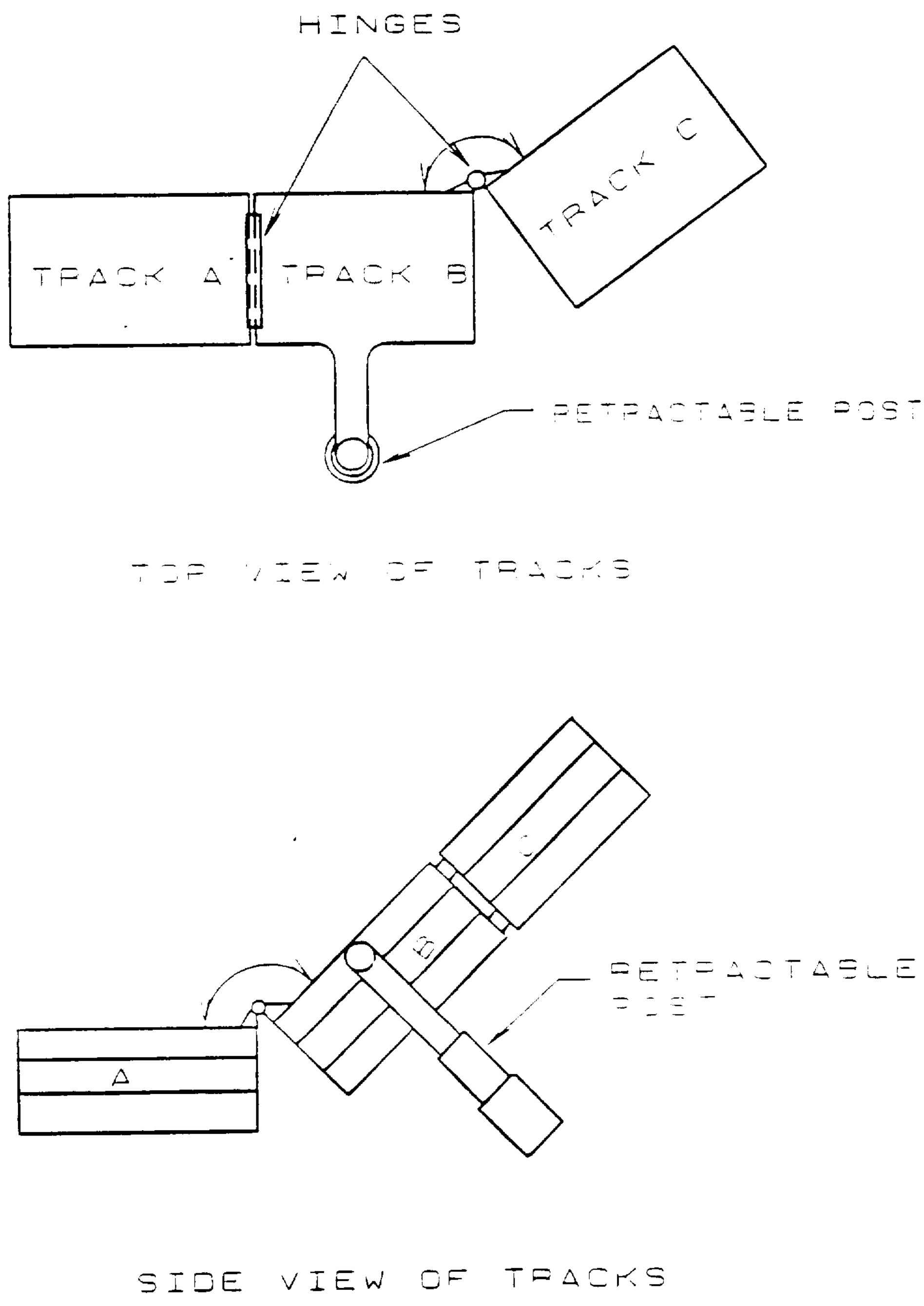

Figure 10   RETRACTION OF TRACK

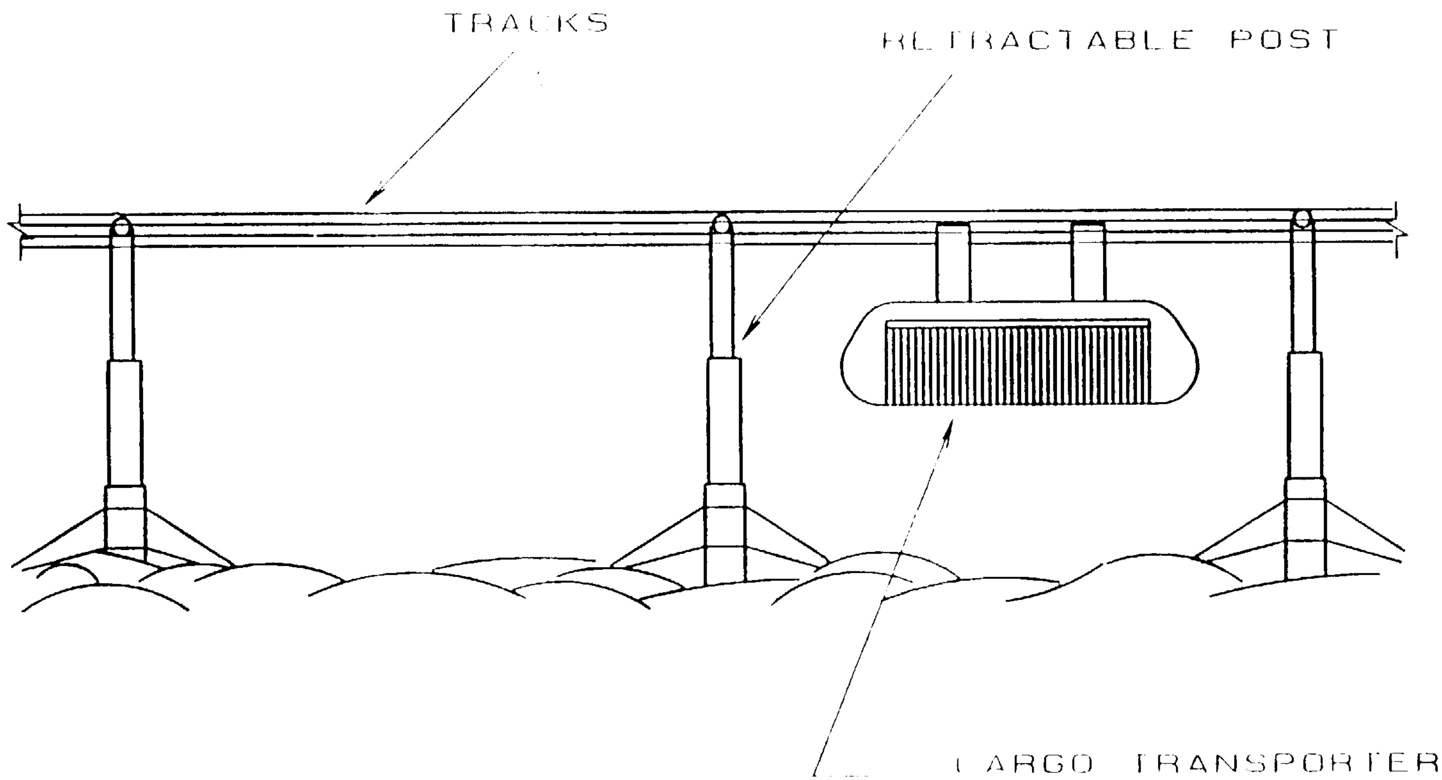

Figure 11 SELF-PROPELLED OVERLAND SUSPENSION SYSTEM

3. Automation and teleoperation are simplified since the system is guided by rail.

4. Several vehicles can be operated on the system at the same time.

Disadvantages

1. Extensive disassembly and assembly is required for relocation.

2. System disassembly and assembly requires extensive power.

3. Extensive material needs cause high system weight and volume.

Winch-Driven Overland Suspension System. The winch-pulled system requires that a cable be attached to the suspended cargo transporter, looped around the system, and attached to the transporter's other side. The cable is driven by a winch, pulling the cargo towards the intended destination either forward or backward (see Figure 12).

Advantages

1. The system avoids creating lunar dust clouds, which can enter between moving parts and promote wear.

2. The system can traverse rough terrain.

3. Automation and teleoperation are simplified since the system is guided by rail.

4. Several transporters can operate at the same time.

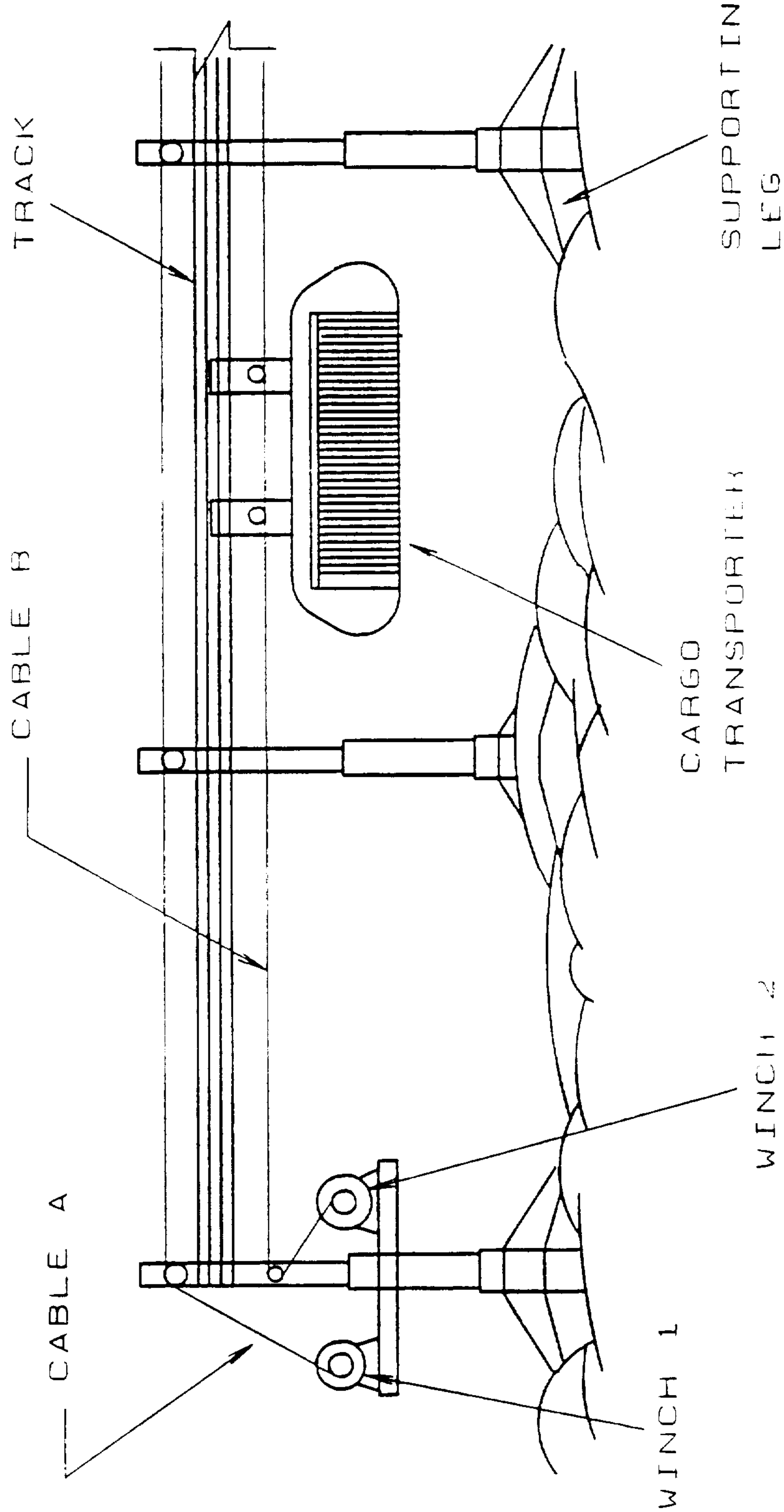

Figure 12: WINCH DRIVEN OVERLAND SYSTEM

5. The power supply and motor remain in one central location.

Disadvantages

1. Extensive disassembly and assembly is required for relocation
2. System disassembly and assembly requires extensive power.
3. Extensive material needs cause high system weight and volume.

SURFACE RAIL SYSTEM

The surface rail system includes any rail or track system that is laid over the lunar surface and guides a vehicle that carries cargo from one site to another. The vehicle can roll on wheels or be magnetically levitated (see Figures 13 and 14). Power to the vehicle is supplied by stored electrical energy, and in the case of magnetic levitation, power to the rail originates from the power plant.

The system is semi-permanent. A rail is laid down completely between two sites, yet it can be disassembled and relocated. This procedure of disassembly and assembly, however, requires the use of an autonomous vehicle to carry the rail, and astronauts or robots to lay and connect it.

Wheeled Surface Rail System. The rollers or wheels of this system roll along grooves in the surface rail which may have one of several configurations designed for stability and control. An on-board

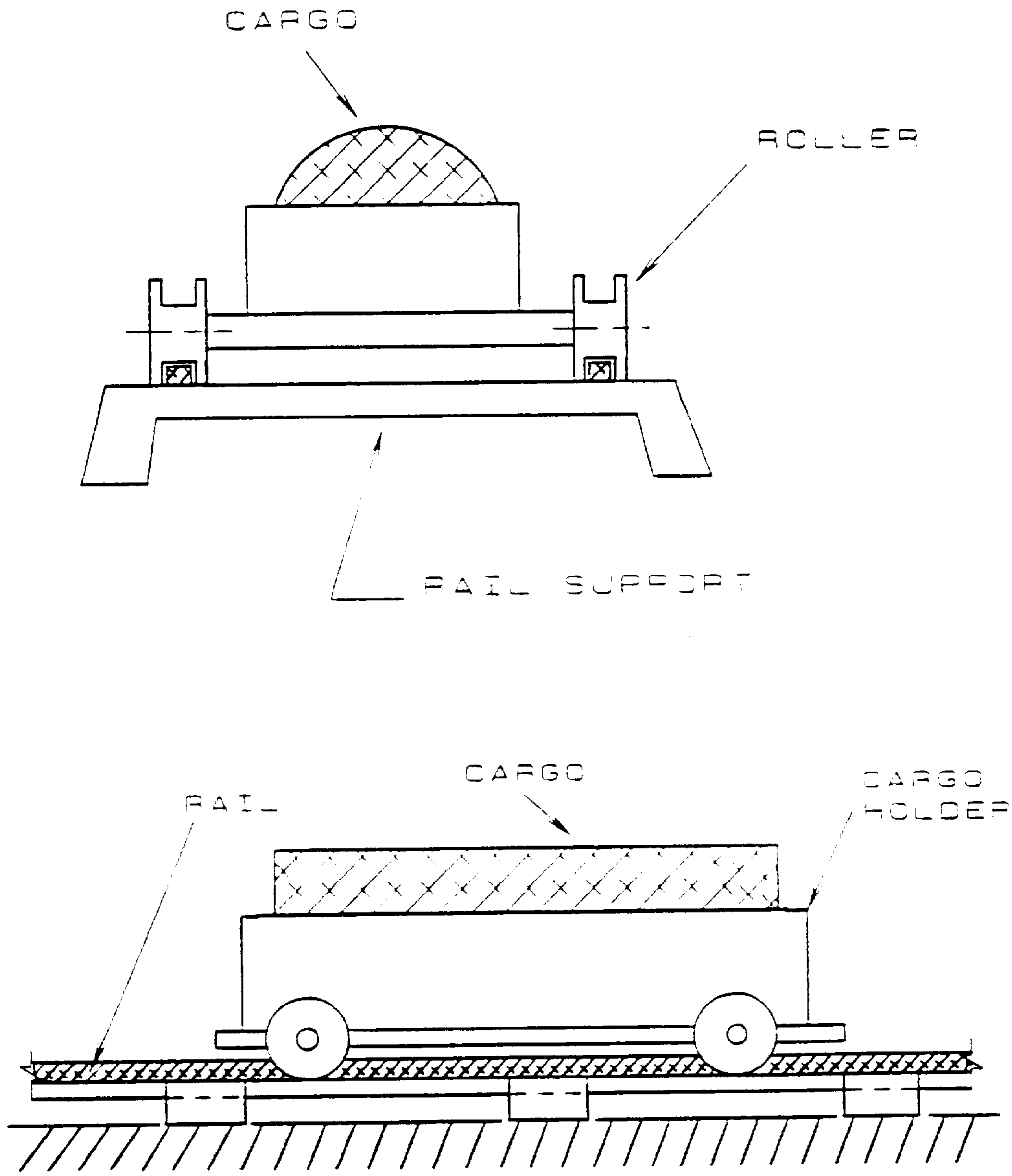

Figure 13 SURFACE RAIL SYSTEM

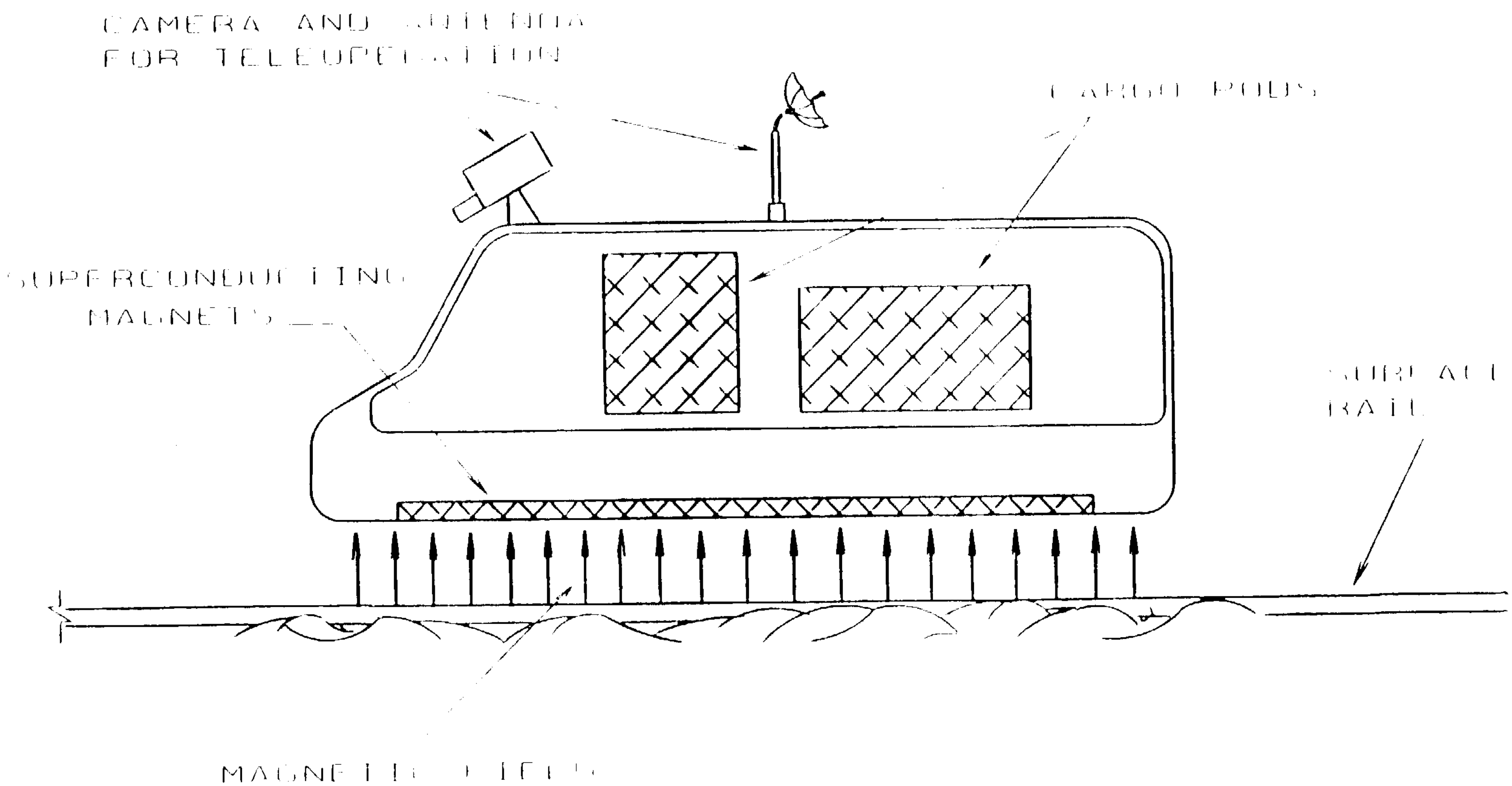

Figure 14 MAGNETIC LEVITATION OF VEHICLE OVER SURFACE RAIL

battery supplies energy to a motor to propel the vehicle along the track.

Advantages

1. Because of stable control, moderate speeds are possible.

2. Harmful dust clouds are not created since the vehicle does not come into contact with the ground.

3. Automation and teleoperation are simplified since the system is guided by rail.

4. Several vehicles can be operated on the system at the same time.

5. The simple meçhanical structure has few moving parts and is therefore reliable.

6. Simple, light-weight vehicles offer low power requirements.

Disadvantages

1. Extensive rail laying is required.

2. Extensive disassembling and assembling of the rail consumes large amounts of power.

3. Total system weight and volume is large because of the amount of rail involved.

4. The system can only traverse light to moderate terrain.

Magnetically Levitated Surface Rail System. A levitated surface rail system operates on the same principles as earth-bound magnetically levitated high speed trains. The vehicle glides over the track levitated by the repelling forces of the magnetic fields in the rail and vehicle. The suspension is created between vehicle magnets and the electrically conducting track. A time varying magnetic field eminating from the track propels the vehicle forward or backward.

Advantages

1. Because of stable control, moderate speeds are possible.
2. Harmful dust clouds are not created since the vehicle does not come into contact with the ground.
3. Automation and teleoperation are simplified since the system is guided by rail.
4. Several vehicles can be operated on the system at the same time.
5. Wear is not a factor since the vehicle does not contact the rail.

Disadvantages

1. Power requirements are high.
2. Extensive track laying is required.
3. Extensive disassembling and assembling of the rail consumes large amounts of power.
4. Total system weight and volume is large because of the amount of rail involved.
5. The system can only traverse light to moderate terrain.

The seven designs were compared in a decision matrix to identify the best design according to certain design criteria such as weight, manpower, safety, power consumption, portability, and reliability. Two modes of decision were considered: at the system level (among the three modes of transportation) and at the subsystem level (among the designs within the modes of transportation). The interaction with other lunar base systems such as the cargo loader and unloader were also taken into account in the decision matrix.

DESIGN SOLUTION

The Self-Repositioning Track Vehicle (SRTV) best meets the design criteria of the seven designs considered. The tool used to identify the best design among the alternatives was a decision matrix where each design is judged according to fifteen design criteria (see Appendix A). For the remainder of this section, the operation of the SRTV is explained, the assumptions for operation are discussed, six areas of design emphasis are explained, and a comparison with the lunar roving vehicle is made.

OPERATION OF THE SRTV

The SRTV consists of a vehicle that rolls over a series of interconnected track sections. Once a track section has been traversed by the vehicle, it is picked up off the ground, brought forward on a conveyor belt, and placed onto the ground in front of the vehicle. The vehicle moves on wheels over the tracks and is capable of either forward or backward motion. Cargo is stored in the cargo bay between the vehicle chasis and the upper platform on which the track sections are brought forward.

The SRTV is shown in Figure 15, and its operation following the lettered steps in the figure is as follows:

1. A track section is placed onto the ground in front of the approaching vehicle at point A.

2. The vehicle rolls over the track section.

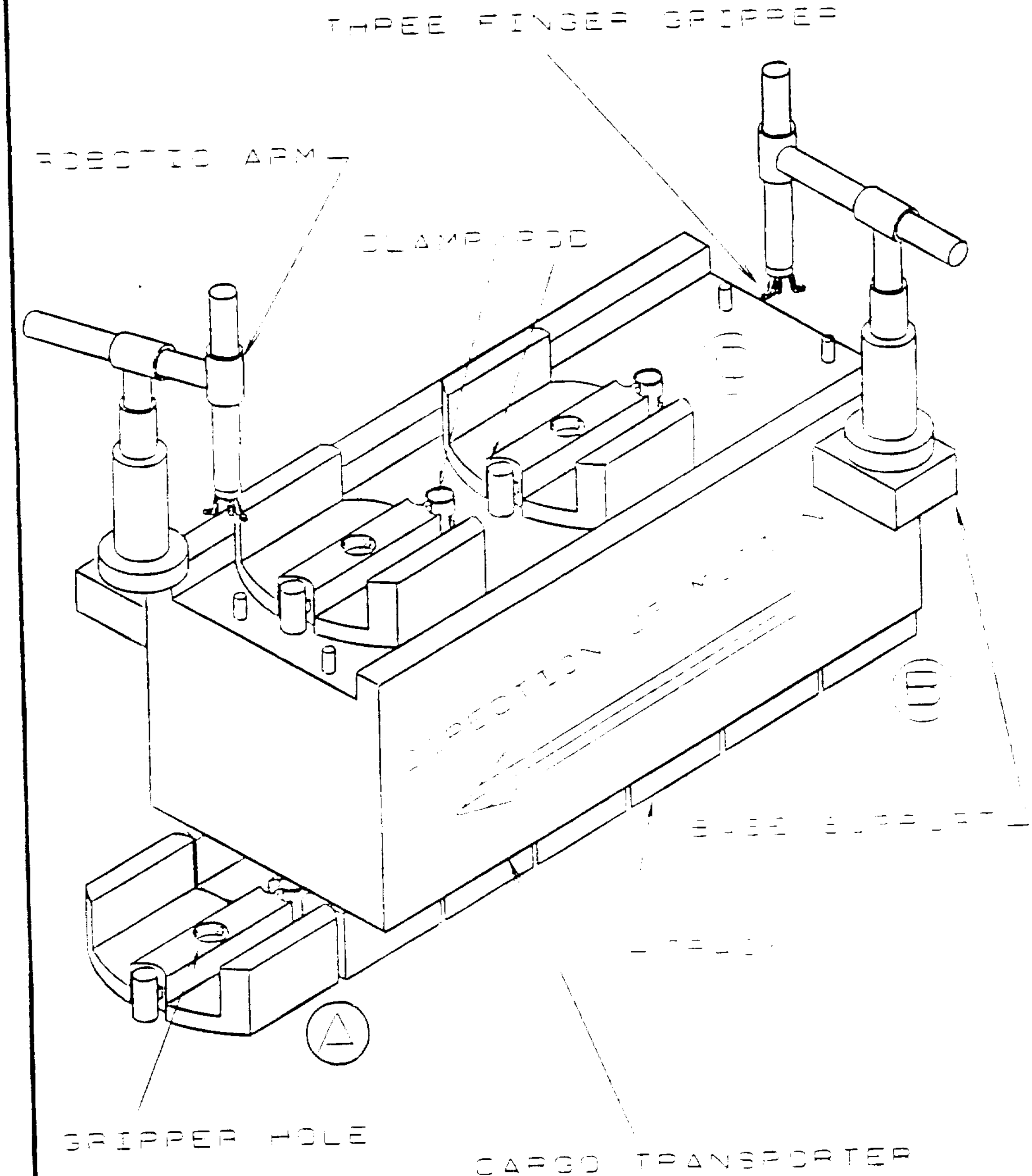

Figure 15 SELF-REPOSITIONING TRACK VEHICLE

3. Once the vehicle has passed over the track section at point B, the rear robotic arm lifts the track off the ground and onto the platform above the cargo bay.

4. The track sections are pulled forward at point C.

5. The forward robotic arm places the track section onto the ground in front of the vehicle and the cycle is repeated.

ASSUMPTIONS

The assumptions made in generating the design of the SRTV are made to simplify the vehicle design and allow for cutting edge technology to be used in making an advanced system. The assumptions are as follows:

1. The surrounding terrain is flat and void of a high density of rocks and holes whose diameters are larger than 0.1 meters.

2. Teleoperation and automation technology is available.

3. Robotics technology is available.

4. A lifting system loads and unloads cargo onto and off of the vehicle.

DESIGN EMPHASIS

The team has directed its concentration into six areas of the SRTV design:

1. Track Configuration and Interconnecting,

2. Track/Vehicle Interface (suspension, driving and guiding wheels),

3. Robotic Arm Motion and Operation.

4. Materials.

5. Teleoperation Systems, and
6. Cargo Bay Dimensions.

Track Configuration. The track serves several purposes. First, the interface between vehicle and riding surface is controlled, reducing rolling friction. Second, dust clouds are kept away from moving parts, mainly the wheel assemblies. Third, teleoperation is reduced in complexity because of the track-guided configuration.

The track system is comprised of nine sections. Each track section consists of a rod and clamp coupler, a middle guiding rail, two side-walls, and cleats (see Figure 16). Each track section is 1 meter long, 1.2 meters wide, and 0.3 meters tall.

As each track section is set down in front of the vehicle, the robotic arm slides the male connection into the female connection of the previous track section. When the track sections are flush with each other, an actuator locks the joint preventing any separation or vertical movement of track sections, yet allowing slight twists and bends to account for surface irregularities. As the rear wheel assembly of the vehicle passes completely over a track section, the actuator releases as it senses no weight on the track. The section is then picked up by the rear robotic arm.

The track section contains a male connector (rod) at one end and a female connector (clamp) at the other (see Figure 17). The torque produced on the coupling by unevenly laid track sections tends to unlock the clamp. To compensate for a maximum offset angle of 5 degrees between two adjacent track sections and avoid

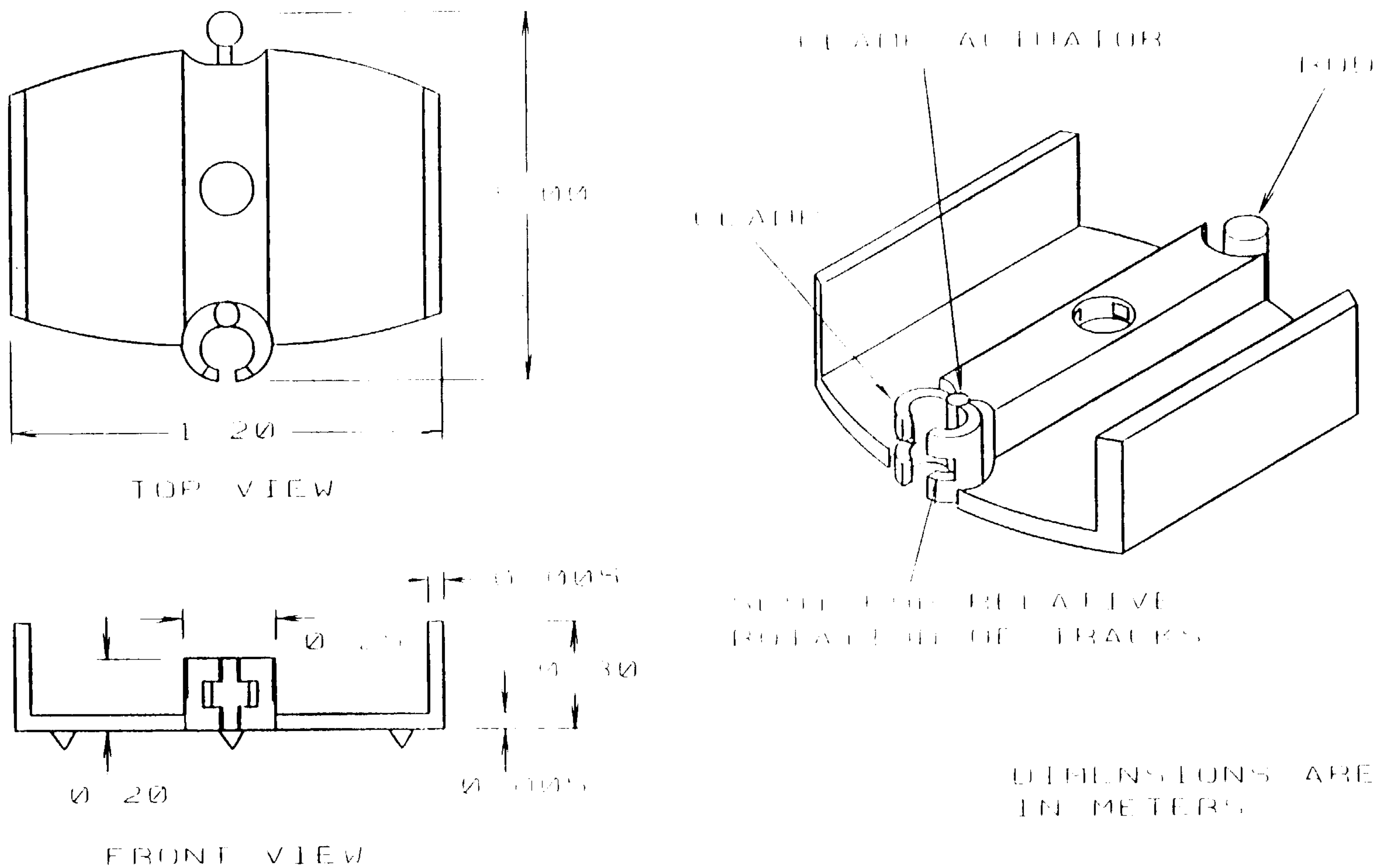

Figure 16 TRACK OVERALL DIMENSIONS

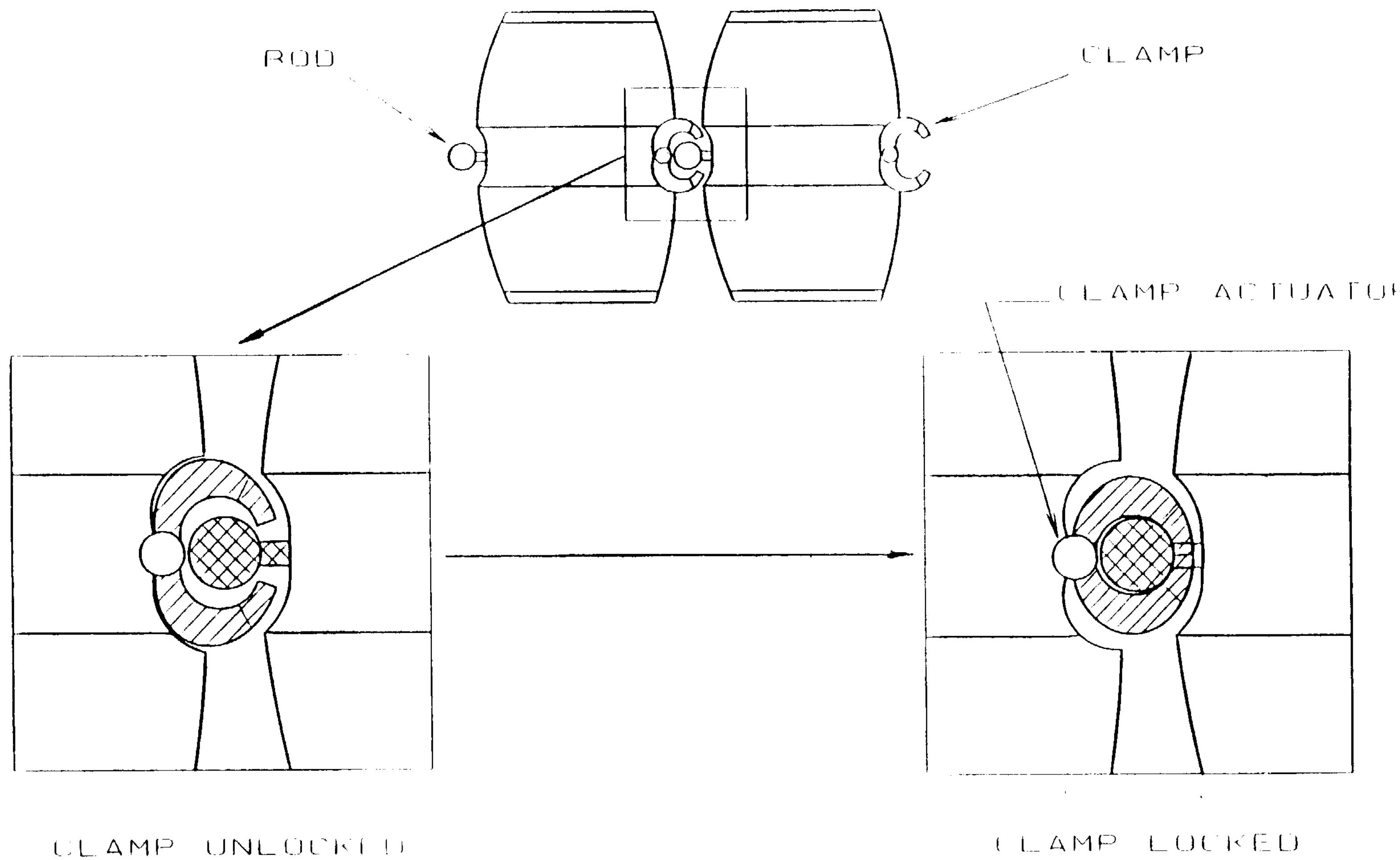

Figure 17 TOP VIEW OF THE TRACK CONNECTION

clamp unlocking during operation, a counter moment of 250 N-m at the clamp balances the torque (see appendix C).

The direction of vehicle travel is controlled by the angle at which the robotic arm sets a track section down relative to the previous track section. The slot in the clamp allows the rod of the next track section to be placed at an angle. The actuator locks the track sections at this angle. Due to sudden changes in vehicle direction and the inherent gap between track sections during curved travel, the relative angle between track sections is limited to ten degrees or less.

The center guiding rail on the track serves two functions. Its primary function is to guide the wheel assemblies along the track. It also serves as a connecting point for the robotic arm grippers.

As a protection against the intrusion of dust, a small, thin wall is designed on each side of the track. These walls protect the wheel assemblies and other moving parts on the vehicle chasis.

Protruding from the underside of each track section are cleats which are designed to anchor the tracks to the lunar surface during operation. This securing action is important especially in vehicle turning as significant lateral forces tend to straighten the track.

Track and Vehicle Interface. The track and vehicle interface includes the track, wheel assembly, and suspension system (see Figure 18). The vertical shafts of both wheel assemblies are located on the undercarriage 1.5 meters from the front and from the rear of the vehicle. Each wheel assembly consists of two driving wheels and two

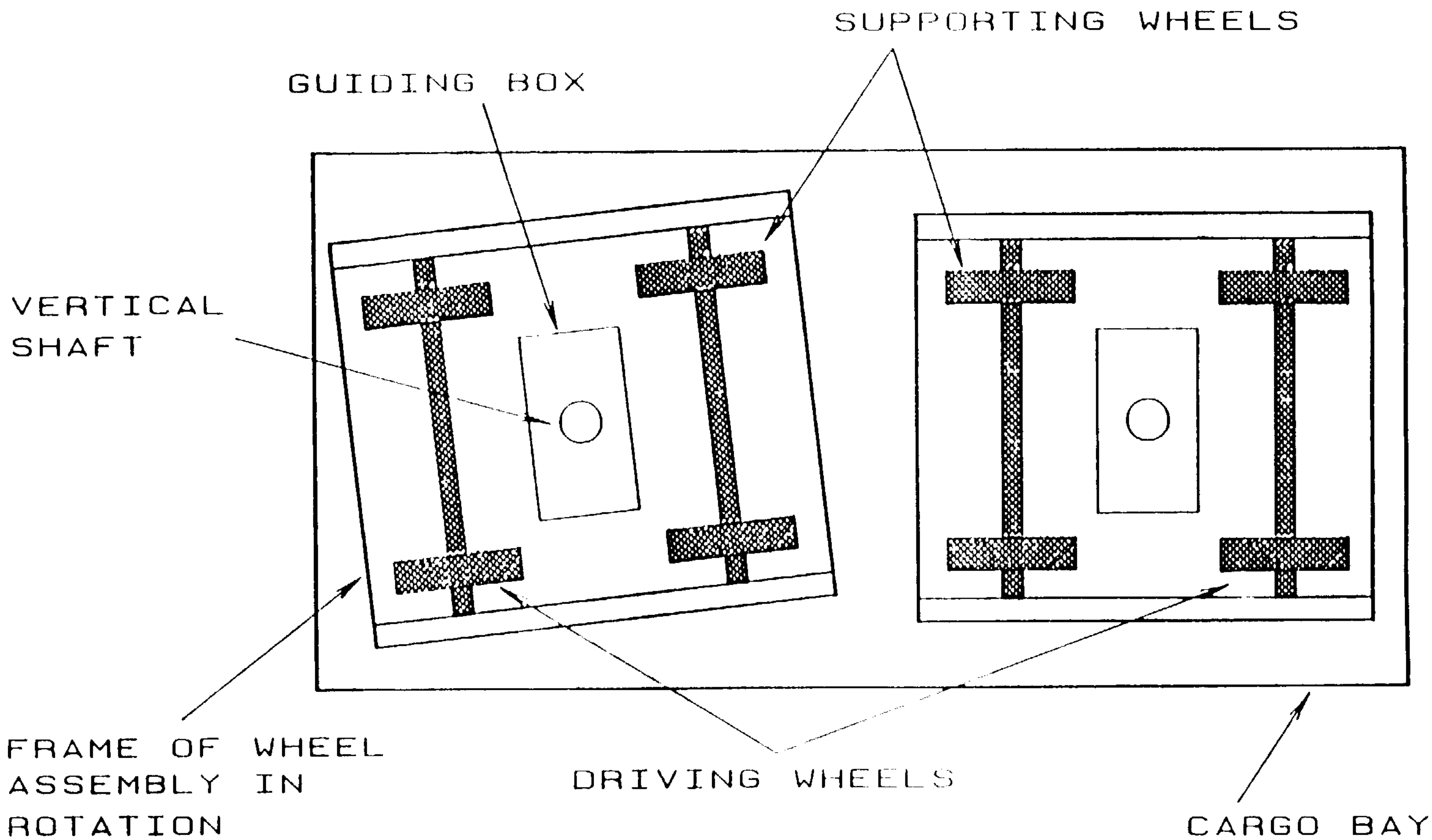

Figure 18: TOP VIEW OF THE VEHICLE
WHEEL ASSEMBLIES

non-driving, supporting wheels for a total wheel count of eight. Each wheel assembly has a common frame rigidly connecting the driving and supporting wheel axles. This frame attaches to a vertical shaft which allows rotation of the wheel assembly relative to the vehicle during curved motion.

The driving and supporting wheels have the same configuration and consist of titanium wheels attached to the ends of a 0.8 meter axle, with the driving axle geared to an electric motor (see Figure 19). The two parallel axles are separated a distance of 1.3 meters so that the vehicle load is spread over two track sections per wheel assembly at all times. Both sets of wheels can never cross the track gap at the same time.

Attached to the wheel assembly frame beneath the vertical shaft is a "U"-shaped guide which controls the orientation of the wheel assembly (see Figure 20). The guide follows a monorail down the center of the track and supports part of the load when the wheels cross over the gaps between track sections.

The suspension system consists of springs and shock absorbers that are packaged around the vertical shaft of each wheel assembly. The springs and shock absorbers support the load of the vehicle and damp out the effects of surface irregularities. The vibrations caused by surface irregularities affect the positioning precision of the robotic arm and must be quickly damped out.

Due to uneven track sections, an approximately harmonic excitation occurs. Assuming an amplitude of vibration for the SRTV of 0.02 meters and an amplitude of the harmonic excitation of 0.015

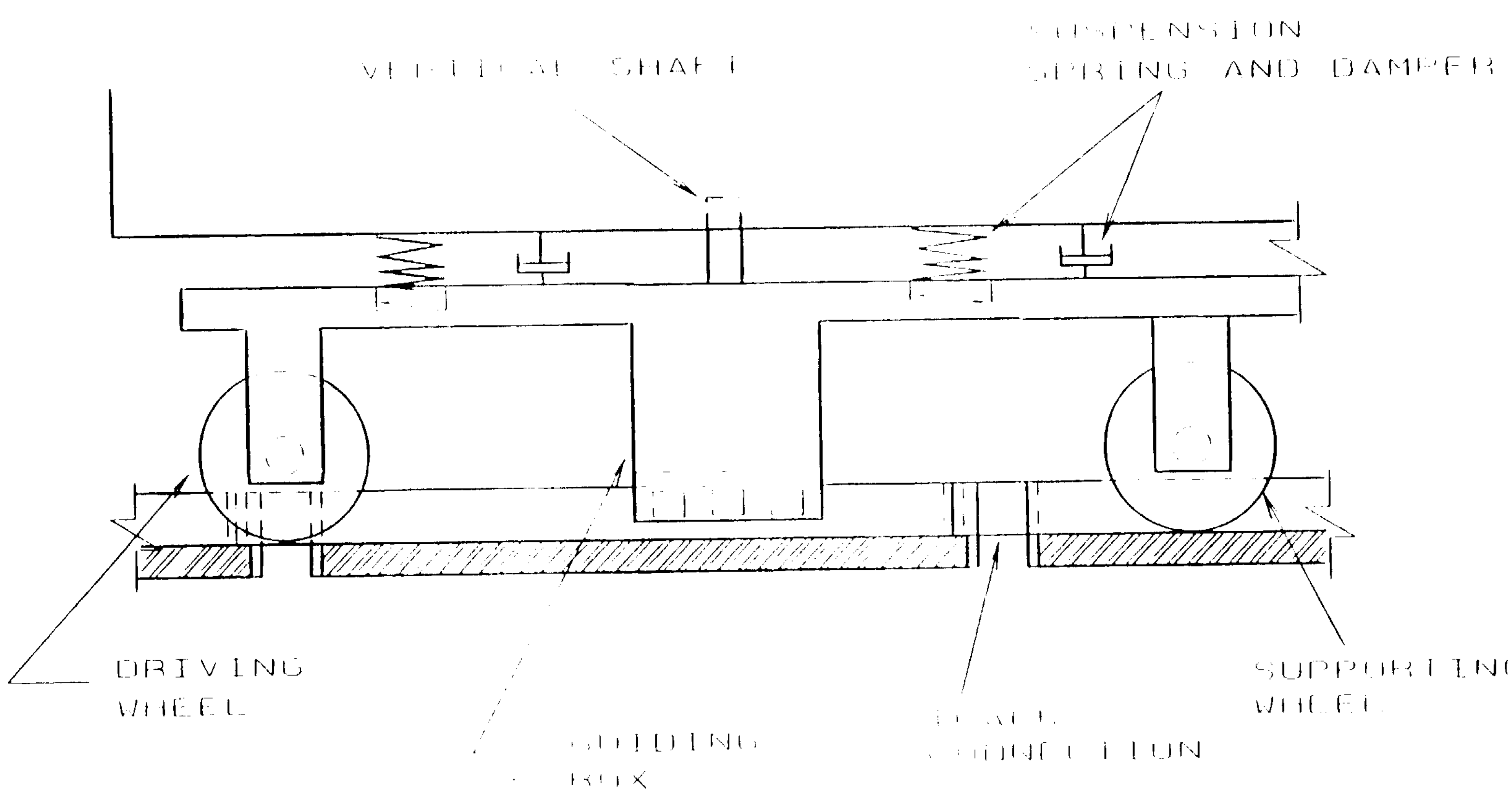

Figure 19: SIDE VIEW OF A SINGLE WHEEL ASSEMBLY

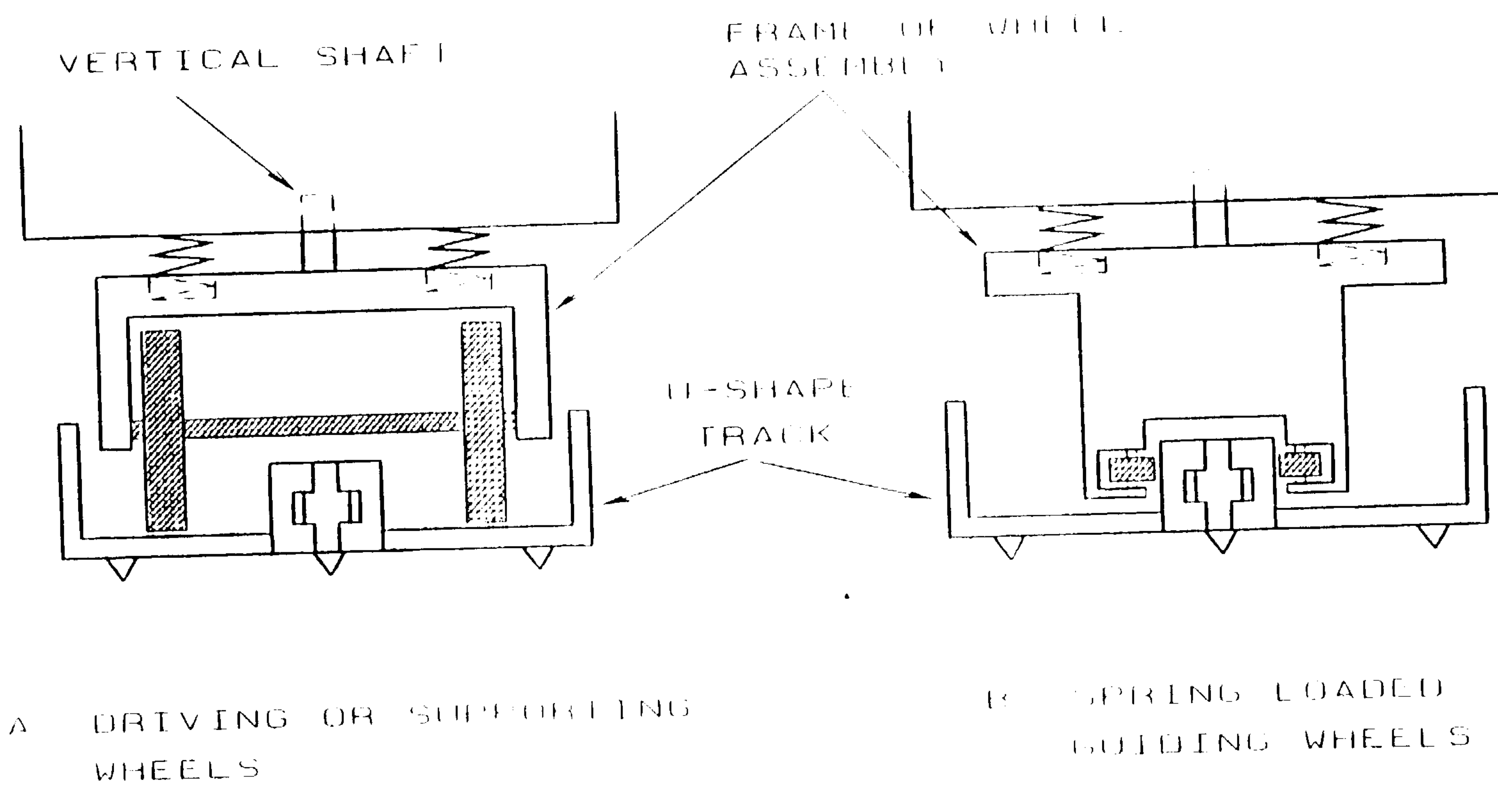

Figure 20. FRONT VIEWS OF WHEELS INTERFACE WITH TRACK

meters, a damping ratio of 0.6 is required. The damping ratio of 0.6 causes the vehicle to reach equilibrium quickly, therefore enhancing the precision of the robotic arms as they lower and raise track sections.

Robotic Arms. Two robotic arms are used to lift and lower the track sections between the ground and the platform above the cargo bay. The arm on the vehicle front lowers the track sections to the ground, while the rear arm raises the track sections from the ground. Both are configured the same way and follow the same motion of travel, providing the versatility of forward and backward motion.

The number of degrees of freedom required to lift or lower a track section between the ground and upper platform is five. Each robotic arm consists of a base support, four linkages, two revolute joints, and three prismatic joints (see Figure 21). Precise control of the arm is achieved through high natural frequency linkages by using materials with high stiffness.

At the free end of the robotic arm is a three-fingered gripper which grasps the track section for travel between the ground and upper platform (see Figure 22). The three fingers of the gripper fit into slots in the track section center and expand. With a vehicle cruising speed of 5 kilometers per hour, the robotic arms will raise and lower the track sections with an average velocity of 2.8 meters per second (see Appendix E).

The motion of the robotic arms is controlled by an on-board computer. The repetitive motions of raising and lowering the track

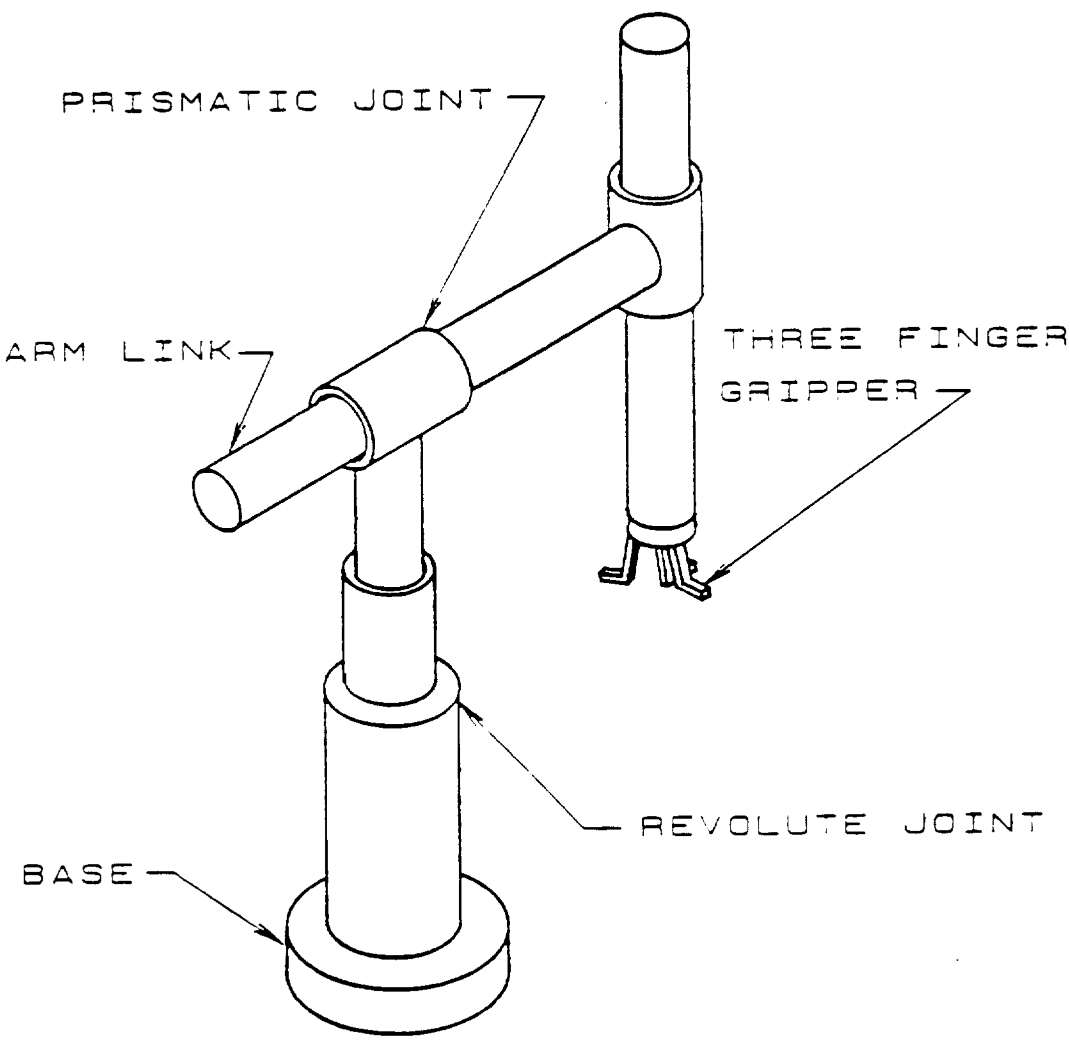

Figure 21: ROBOTIC ARM

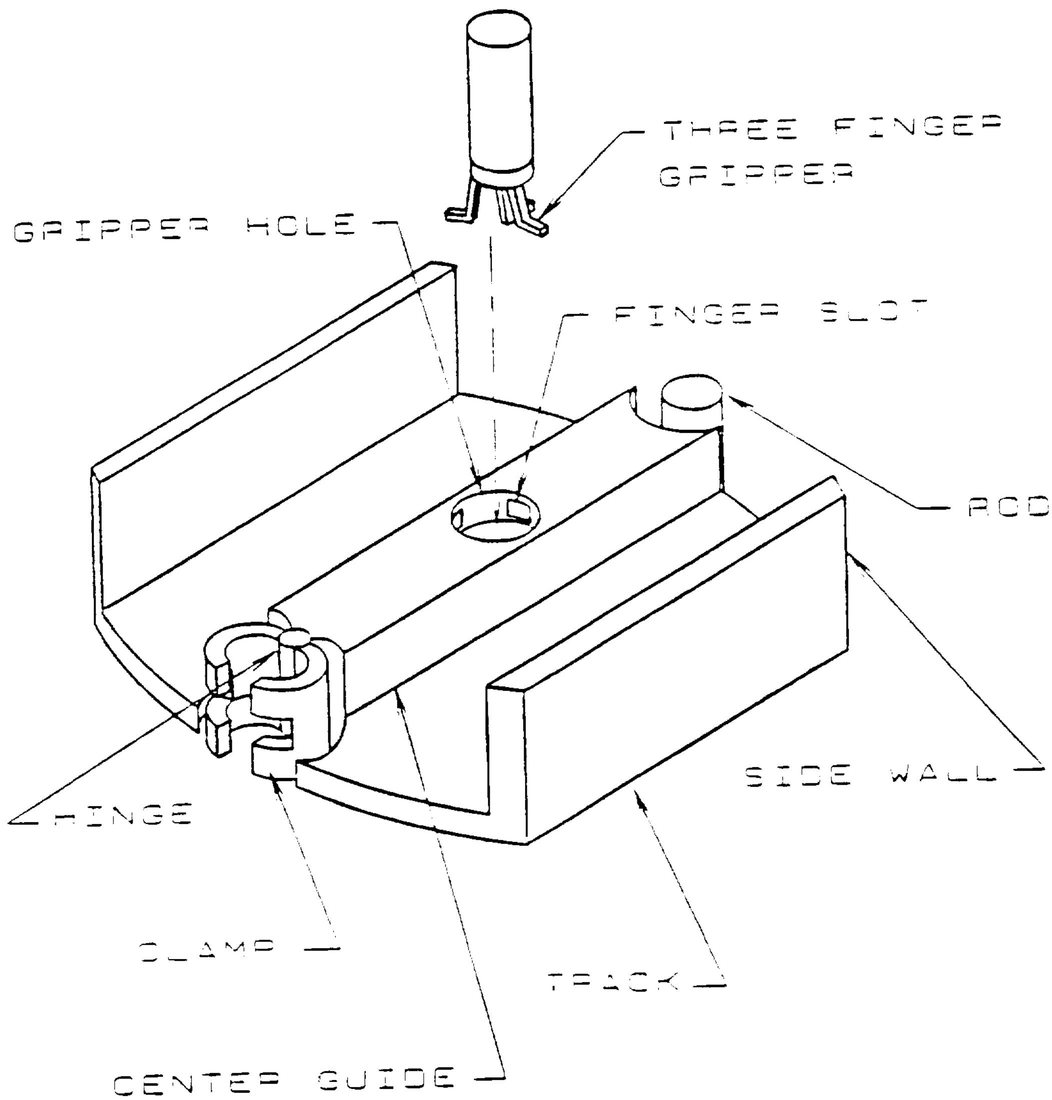

Figure 22 GRIPPER AND TRACK INTERFACE

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are pre-programmed while any unexpected motions, such as locating a misplaced track, can be inputted into the computer from teleoperation signals.

Materials. The team chose titanium for all structural members, robotic arms and the tracks. Aluminum is used for the shell of the cargo bay. These two materials are chosen because of their high strength to density ratio and because they have been successfully used in previous NASA space craft.

Titanium has favorable physical properties such as low density, high strength, and high stiffness which makes it preferable for supporting structures, but is difficult to machine and requires an inert atmosphere for welding. In the lunar environment where temperatures vary from -171 degrees Celsius to +111 degrees Celsius, titanium is an ideal material because of its low thermal expansion and good high-temperature strength (see Appendix F).

Aluminum is light weight and high strength but lacks the stiffness required by supporting structures. Therefore, the team used it only for the cargo bay's shell. Its low coefficient of thermal expansion and adequate temperature strength are appropriate for the lunar environment.

Teleoperation. The SRTV can either be teleoperated from the lunar base or from earth. Two methods of teleoperation are currently under study at the Jet Propulsion Laboratory in Pasadena, California.

The two teleoperation methods are Computer Aided Remote Driving (CARD) and Semiautonomous Mobility (SAM).

With the CARD method, the SRTV continuously receives travel maps from earth. The speed of the vehicle can be no more than one cm/sec. The vehicle response to operator commands lags by 2.5 seconds because of the earth-moon distance. Therefore, since the operator does not have instantaneous control of the vehicle, the vehicle speed must be kept low to protect the system from striking dangerous or destructive objects.

The team has chosen the SAM method for teleoperation and course mapping for autonomous operation of the SRTV. The sequence of operation is as follows:

1. An orbiting vehicle produces global topographic maps of an area of the lunar base and sends them to earth.

2. On the global topographic maps, an operator designs a path and identifies locations of dangerous areas or obstacles to steer clear of.

3. The global maps and paths are sent to the SRTV's computer which combines them with its local maps to form a revised map.

4. The computer analyses the revised map, determines and records a safe path for the SRTV to travel.

5. The SRTV travels a short distance before receiving another signal from earth.

6. After completing a course, the SRTV operates autonomously following the same course until a new one is specified.

Cargo Bay Dimensions. The dimensions of the cargo bay were determined by the SRTV's maximum payload and size of the cargo. The team set the SRTV's maximum payload at 2500 kg and the maximum cargo size for cylindrical cargo is 1.3 meters in diameter and 5.0 meters in length, and for rectangular cargo, dimensions are 1.2 meters in width, 5.1 meters in length, and 1.4 meters in height. The cargo bay dimensions with these specifications for cargo are 1.6 meters in width, 5.8 meters in length, and 1.6 meters in height (see Figure 23).

COMPARISON WITH LUNAR ROVING VEHICLE

The SRTV is designed to replace the lunar roving vehicle (used in Apollo missions) for cargo transporting within the lunar base. A comparison of the two vehicles follows.

Criteria	Rover	SRTV
Mass (loaded)	708 kg	6000 kg
Manpower Required	YES	NO
Power	3.0 kW	10 kW
Personnel Safety	Good	Excellent
Teleoperation	Difficult	Simpler
Cargo Capacity	500 kg	2500 kg

The primary reasons for replacing the rover are to reduce the chances of astronaut injury and allow them to do more important tasks, which are strong points of the SRTV.

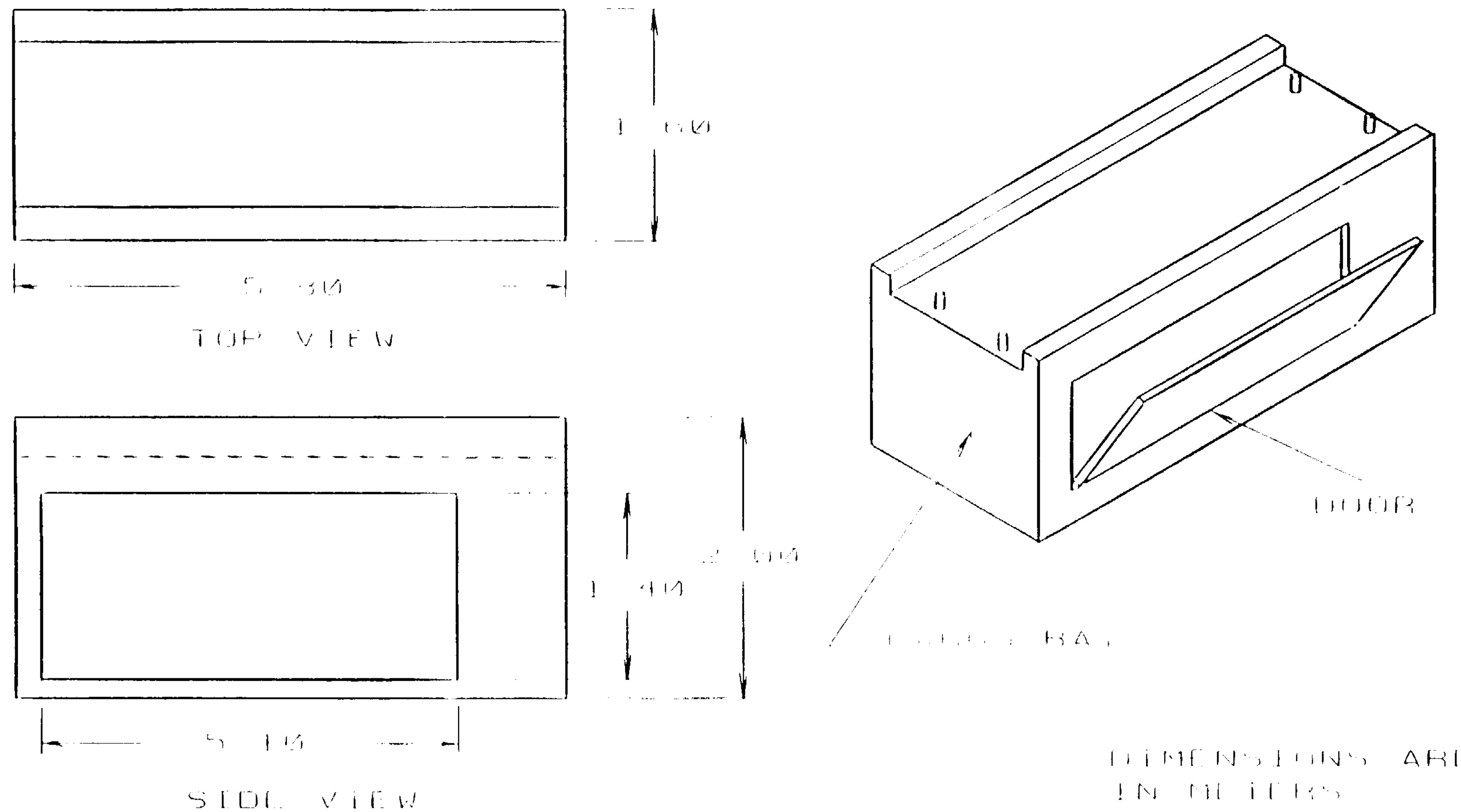

Figure 23. CARGO BAY OVERALL DIMENSIONS

CONCLUSIONS AND RECOMMENDATIONS

The Self-Repositioning Track Vehicle was chosen not only because of its superior benefits over the other design alternatives, but also because it was a new and novel idea that has been researched very little up to this point. The following characteristics show how the design has met the specified design criteria:

1. The SRTV requires no manpower for operation so the chances of injury are reduced and the astronauts are freed to do more important tasks.
2. Empty mass of the SRTV is 3500 kg and fully loaded mass (vehicle and payload) is 6000 kg.
3. When fully loaded, power needs are approximately 10 kW.
4. No system disassembly or assembly is necessary upon relocation to other facilities in the base.
5. With a maximum payload of 2500 kg, the SRTV travels at a top speed of 5 km/hr.
6. The cargo bay has dimensions of 1.6 m by 5.8 m by 1.5 m for a cargo volume of 14 cubic meters.
7. The cargo bay structure is made with titanium as confirmed by stress analysis.

The team has concentrated their design efforts into six areas: track connection, vehicle/track interface, robotics, materials, teleoperation, and cargo bay dimensions. The team recommends further design and investigation into other areas.

The present system design assumes operation over a flat surface so that track sections are flush with one another. Further investigation should be made for operation over rough surfaces when the track sections are laid unevenly.

Use of high-strength, low-density composite materials will reduce overall vehicle mass and power consumption. The team recommends the use of such composites as they are approved for this type of application.

Lunar dust is abrasive and conducive to rapid wearing so all joints connecting moving parts must be protected. A device must be designed to remove the sticky dust from the track section undersides without creating a dust cloud over the vehicle.

The robotic arm operates quickly to lift or lower a track section between the ground and upper platform above the cargo bay. Thus the point of application of the robotic gripper onto the track must be quickly and easily found. A honing device is needed so that the gripper can locate the track and define its orientation when the track is in any position on the ground.

Finally, the team recommends design efforts pointed towards serviceability. Although the vehicle is designed for reliability, maintenance and repair may be necessary. To facilitate the repair of the SRTV, components should be of a modular design for quick and easy removal and replacement.

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APPENDICES

APPENDIX A

DECISION MATRIX

ALTERNATE DESIGNS SELECTION BY DECISION MATRIX

The team used a decision matrix to select the best design from the seven alternatives. The team generated the fifteen most important design criteria to judge the seven alternate designs. Weighting factors were assigned to each criterion with the more important criteria receiving a higher values.

The weighting factors were obtained by using the method of pairs which compares every criterion against all the others with the more important of the two receiving a mark. The number of marks are summed and divided by the maximum possible number of marks. This ratio is the weighting factor.

The designs were compared under each criteria and were given a number from 1 to 10 (best) according to how well they satisfied the particular criterion. This number was multiplied by the weighting factor to obtain a certain number of points. These points were added for each design and the totals compared. The SRTV had the highest number of points, indicating it was the best alternative.

FOLDOUT FRAME /

TABLE A.1: ALTERNATE DE

DESIGN CONSIDERATIONS → / WEIGHTING FACTORS ↘ / ↓ SYSTEMS	DESIGN PARAMETERS: WEIGHT	MANPOWER	POWER	PACKING SPACE	ASS./DISS.	RELOCATION	MAINTENANCE
	0.0901	0.0534	0.1065	0.0656	0.0164	0.0082	0.041
TANK TREAD	9 / 0.8114	10 / 0.5337	3 / 0.3196	8 / 0.5246	10 / 0.1639	10 / 0.0819	5 / 0.24
WHEELS	10 / 0.9016	10 / 0.5337	4 / 0.4262	9 / 0.5901	10 / 0.1639	10 / 0.0819	3 / 0.22
SELF-REP TRACK	8 / 0.7213	10 / 0.5337	8 / 0.8525	7 / 0.4590	10 / 0.1639	10 / 0.08197	7 / 0.25
SELF-PROP OVERLAND SUSP	5 / 0.4508	8 / 0.4269	10 / 1.0656	6 / 0.3934	5 / 0.08196	4 / 0.0328	9 / 0.3
WINCH PULLED OVERLAND SUSP	4 / 0.3605	8 / 0.4269	8 / 0.8524	5 / 0.3279	4 / 0.0656	4 / 0.0328	9 / 0.3
RAIL	6 / 0.541	7 / 0.3736	9 / 0.959	5 / 0.3279	3 / 0.0492	4 / 0.0328	7 / 0.2

FOLDOUT FRAME 2

SIGNS DECISION MATRIX

	DESIGN PARAMETERS								
	THERM. EXP	CARGO SAFETY	COST TRANSP	PERS. SAFETY	DUST FORM.	RELIABILITY	RADIATION PROTECTION	EASE UPLN AUTOM	SUM OF PRODUCTS
	0.08197	0.1066	0.0902	0.1147	0.0154	0.1055	0.0164	0.0820	1.00
3	6 / 0.4918	8 / 0.8525	9 / 0.8115	10 / 1.148	3 / 0.0492	4 / 0.4262	8 / 0.1311	5 / 0.4098	6.96
8	8 / 0.6557	8 / 0.8525	10 / 0.9016	10 / 1.1475	5 / 0.0819	6 / 0.6393	7 / 0.1147	4 / 0.3279	7.75
3	7 / 0.5738	10 / 1.0656	8 / 0.7213	10 / 1.1475	8 / 0.1311	9 / 0.9524	6 / 0.0984	8 / 0.6557	8.25
2	7 / 0.5738	9 / 0.9524	5 / 0.4508	9 / 1.0327	10 / 0.1639	9 / 0.9589	6 / 0.06234	10 / 0.8197	7.74
8	7 / 0.5736	8 / 0.8524	4 / 0.3606	9 / 1.0327	10 / 0.1639	9 / 0.9589	5 / 0.0622	10 / 0.8197	7.26
9	4 / 0.3279	7 / 0.7459	6 / 0.541	8 / 0.918	5 / 0.08156	8 / 0.8524	6 / 0.06234	10 / 0.8197	6.92

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APPENDIX B

WEIGHT AND POWER CALCULATIONS FOR THE SRTV

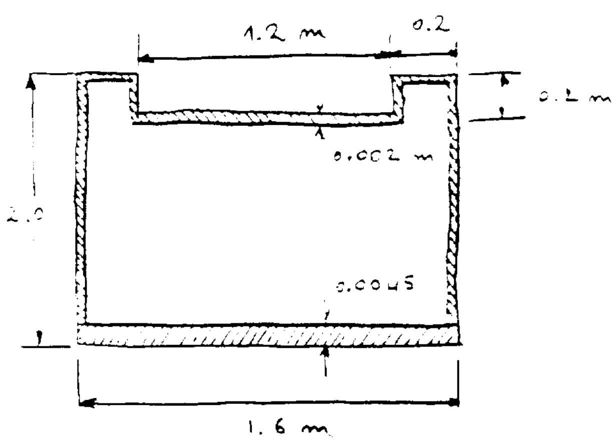
APPENDIX B

WEIGHT AND POWER CALCULATIONS FOR THE CRTV

I. VEHICLE'S WEIGHT

ASSUME :
1. CARGO MASS $M_c = 2500$ kg
2. USE TITANIUM FOR SUPPORTING MEMBERS, TRACKS, ROBOT ARMS
3. USE ALUMINUM FOR CARGO BAY SHELL

CARGO BAY :



FRAME

VOLUME = V

$V = 1.6 \times 0.0045 \times 5.8$

$= 0.042 \ m^3$

SHELL

$V = 0.084 \ m^3$

$$\text{Mass} = M_1 = (0.042 \times \rho_{TIT}) + (0.084 \times \rho_{AL.})$$

$$= (0.042 \times 4400 \ kg/m^3) + (0.084 \times 2800 \ kg/m^3)$$

$$M_1 = 420.0 \ kg$$

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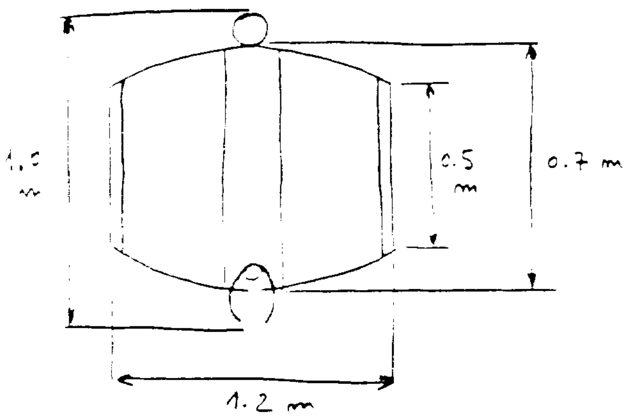
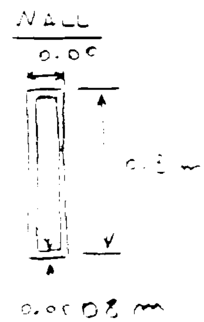
TRACK:

ASSUME: • 9 TRACKS

• WALLS ARE HOLLOW WITH $t = 0.002$ m

• GUIDING RAIL IS HOLLOW WITH THICKNESS $t = 0.0045$ m



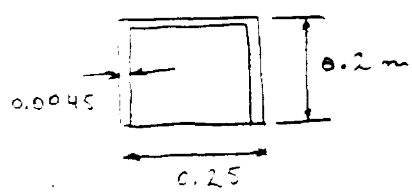


$$V = 9\left[V_{WALLS} - V_{PLATFORM} - V_{COUPLER} - V_{GUIDING\ RAIL}\right]$$

$$= 9\left[0.0003 + 0.004 + 0.0098 + 0.003\right]$$

$$= 0.154 \ m^3$$

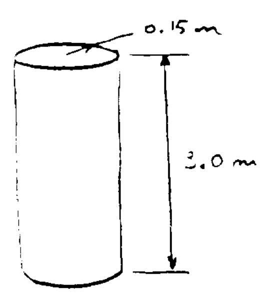
GUIDING RAIL



$$M_{TRACK} = \left(0.154 \times 4400 \ kg/m^3\right) = \boxed{677.0 \ kg}$$

ROBOT ARM

ASSUME LINKS AS FOLLOWS:



$$V \cong \left[\pi \left(\frac{0.15}{2}\right)^2 3 + \pi \left(\frac{0.15}{2}\right)^2 1.5 + \pi \left(\frac{0.15}{2}\right)^2 1.0 \right]$$

$$\simeq 0.194 \ m^3$$

$$M_{ROBOT\ ARMS} = 0.194 \times 4400 = \boxed{854.0 \ Kg.}$$

ASSUME INSTRUMENTATION (COMPUTER – MOTOR – ETC.)
– DRIVE TRAIN + SUSPENSION MASS IS :

$$M \cong 1500 \ Kg$$

THE TOTAL MASS OF SYSTEM (NO LOAD) = $\boxed{M = 3451 \ Kg}$

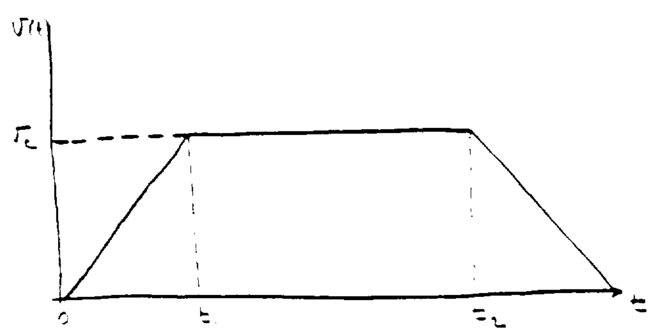
FULLY LOADED $\boxed{M \cong 6000 \ Kg}$

∴ TOTAL WEIGHT (MOON WEIGHT)

$$W = \frac{6000 \times 9.81}{6} = \boxed{9810 \ N.}$$

II. VEHICLE POWER :

VEHICLE VELOCITY



ACCELERATION IS CONSTANT FROM 0 TO t_1 WHERE t_1 = 7 min. DECELERATION TAKES 7 MIN ALSO.

$$\int_{v_0}^{v} v\,dt = a\int_{t_0}^{t} dt \Rightarrow a = \frac{v}{t}$$

$$= \frac{1.38\,m/s}{400}$$

$$= 0.00345\,m/s^2$$

SINCE a IS CONSTANT IN THE FIRST PORTION OF THE GRAPH THEN

$$s = s_0^{\,0} + v_0 t^{\,0} + \frac{1}{2} a t^2$$

$$s = \frac{1}{2}\, 0.00345\,(400)^2 = 276\ m$$

$$F = ma = 6000\,kg\,(0.0034) = 20.4\ N$$

$$\text{WORK} = Fs = 20.4 \times 276 = 5.6\ KJ$$

$$\text{POWER} = 5.6\,KJ / 400 = \boxed{14\ W}$$

(POWER PROVIDED TO ACCELERATE)

POWER PROVIDED FOR ROLLING.

R = RADIUS OF WHEELS = 0.3 m

$$I = 6000\,kg \times (0.3)^2 = 540\ kg\cdot m^2$$

$$\omega = \frac{V}{R} = \frac{0.694}{0.3}\,m/s = 2.31\ RAD/s$$

$$\Delta\lambda = \text{CHANGE IN ENERGY} = \frac{1}{2} M v^2 + \frac{1}{2} I \omega^2$$

$$\Delta u = \frac{1}{2}\left[6000\,(0.3)^2 + 540\right](2.31)^2$$

$$= 2884.1 \ \text{N.m}$$

$$\Delta u = F.\,s = 2884.1$$

$$F = \frac{2884.1 \ \text{N.m}}{4448 \ \text{m}} = 0.65 \ \text{N}$$

$$\text{POWER} = F \times V = 0.65 \times .38 \ \text{m/s} = \boxed{1.0 \ \text{W.}}$$

<u>POWER FOR ROBOT:</u>

IF THE VEHICLE RIDES AT 5.0 Km/H WE ESTIMATE THAT THE ROBOT MUST RUN AT A SPEED OF 10 Km/H.

1. <u>VERTICAL MOTION</u>

$$\text{P.E.} = \text{POTENTIAL ENERGY} = Mgh$$

M = MASS OF TRACK + ROBOT LINK

H = HEIGHT OF TRANSPORT

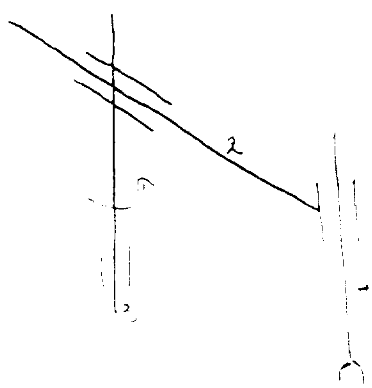
$$\text{P.E} = 360\,\text{Kg} \times \frac{9.81}{6} \times 2.8 = 1648.0 \ \text{J}$$

$$\text{POWER} = \frac{\text{PE}}{t} = \frac{1648}{0.56 \ \text{sec}} = 2940 \ \text{W}$$

FOR BOTH ROBOT $\boxed{\text{POWER} = 5.9 \ \text{KW}}$

2. <u>ROTATIONAL MOTION</u>

T = KINETIC ENERGY = $I \alpha \, d\theta$



ASSUME: α_2 = 0.22 RAD/S² (ANGULAR ACCELERATION OF LINK 2)

$\Delta\theta_2$ = 0.927 RAD

$I = M R^2$

WHERE M = MASS OF PART OF LINK 2 + MASS OF LINK 4 + MASS OF TRACK

R = HORIZONTAL RADIUS OF LINK 2 ROTATING AROUND LINK 3.

T = (644 [illegible] kg)(0.2[illegible])² × (0.22 [illegible])(0.9[illegible] rad)

= 7.0 J

POWER = $\frac{T}{t}$ = $\frac{7.0 \text{ J}}{0.72 \text{ sec}}$ = 10 W

FOR THE TWO ROBOT $\boxed{\text{POWER} = 20 \text{ W}}$

TOTAL POWER $\boxed{P \cong 6.0 \text{ KW}}$

APPENDIX C

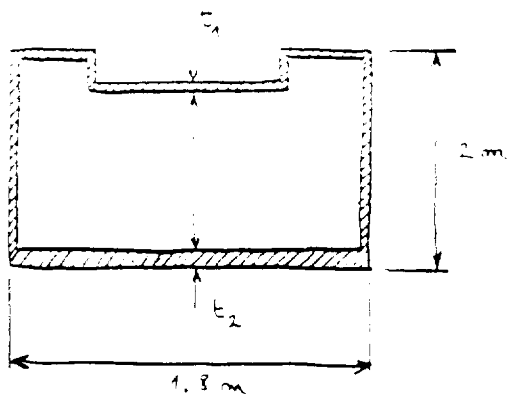
STRUCTURAL ANALYSIS OF THE CARGO BAY,

TRACK, AND TRACK CONNECTING JOINT

APPENDIX C

STRUCTURAL ANALYSIS OF CARGO BAY, TRACK AND TRACK CONNECTING JOINT.

1. DETERMINATION OF CARGO BAY DIMENSIONS



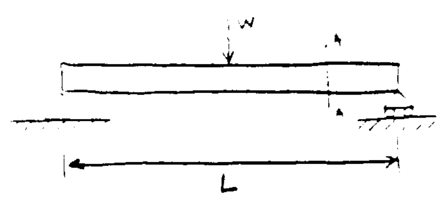
(THICKNESS OF SHELL AND SUPPORTING STRUCTURE)

GIVEN : $L = 1.3$ m

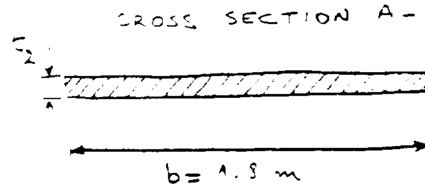
MASS $\cong$ 3000 Kg

FOR TITANIUM $\sigma \cong 1000$ MPA

FRAME :



CROSS SECTION A – A



$$W = \frac{3000 \text{ kg} \times 9.81}{6} = 4905 \text{ N}$$ (WEIGHT)

$$I = \frac{b\,t_2^3}{12} = \frac{1.8\,t_2^3}{12}$$ (MOMENT OF INERTIA)

$$\sigma_{MAX} = \frac{M\,y}{I}$$ (BENDING STRESS)

$$M = \frac{W\,L}{4} = \frac{4905 \times 1.3}{4} = 1594 \text{ N.m}$$

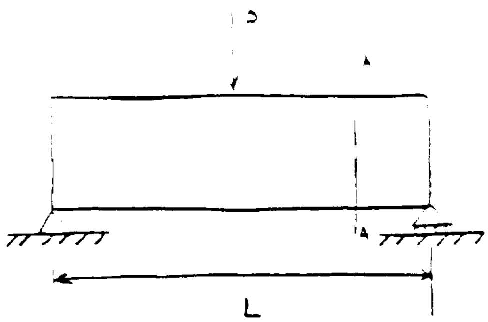
$$\sigma_{MAX} = \frac{1594 \times t_2}{\frac{1.8\ t_2^3}{12}} = 1000\ \text{MPA}$$

$\Rightarrow\ t_2 = 0.0033\ m$

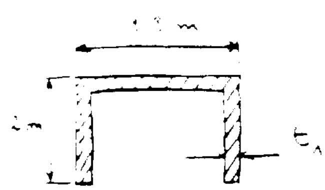
FOR SAFETY

$$\boxed{t_2 = 0.0045\ m}$$

SHELL :



CROSS - SECTION A - A



P = WEIGHT OF TWO TRACK PLACE AT EACH TIME ON TOP OF CARGO BAY

$$\sigma_{MAX} = \frac{M\ y}{I} = \frac{P\ (4)}{1.3} \times \frac{(0.6304\ m)}{(0.0054\ m^4)} = 1000\ \text{MPA}$$

$\therefore\ P = 2.42 \times 10^6\ N$ FOR $t_1 = 0.002\ m$

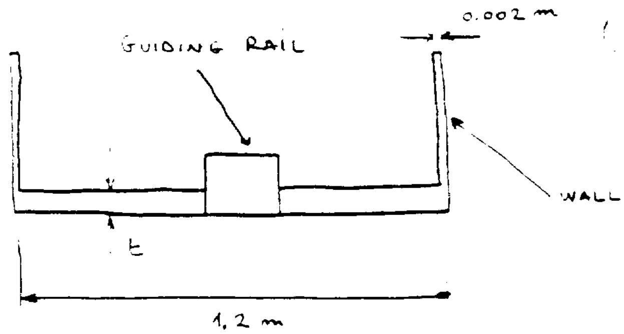
$P = 2.42 \times 10^6\ N$ CORRESPOND TO MASS $= 1.5 \times 10^6\ Kg$

SINCE THE TOTAL MASS OF TRACKS IS LOWER THAN $1.5 \times 10^6\ Kg$

$\Rightarrow\ t_1 = 0.002\ m$

2. DETERMINATION OF TRACK THICKNESS (t)

(USING TITANIUM)



ASSUME

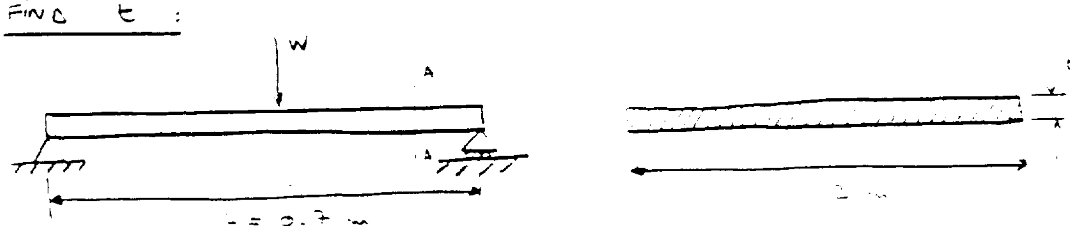
WALLS ARE HOLLOW WITH THICKNESS OF 0.002 m

GUIDING RAIL IS HOLLOW WITH THICKNESS OF

= 0.0045 m

$\sigma_{TITANIUM} \cong 1000\ MPA$

FIND t :



$$W = \frac{3000\ kg \times 9.81}{6} = 4905\ N$$

$$M = \frac{WL}{4} = \frac{4905 \times (0.7\ m)}{4} = 858.4\ N \cdot m$$

$$\sigma_{MAX} = \frac{My}{I} = \frac{858.4 \times t}{\frac{1.2\ t^3}{12}} = 1000\ MPa$$

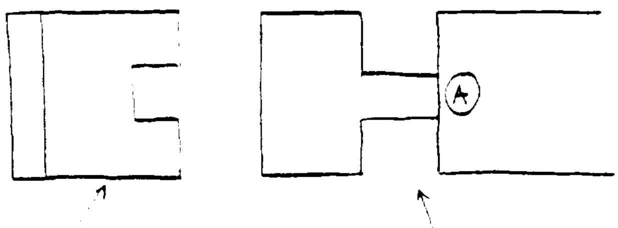
$t = 0.003\ m$

FOR SAFETY WE ARE GOING TO HAVE $\boxed{t = 0.0045\ m}$

3. TRACK CONNECTING JOINT.

a. STRESSES :

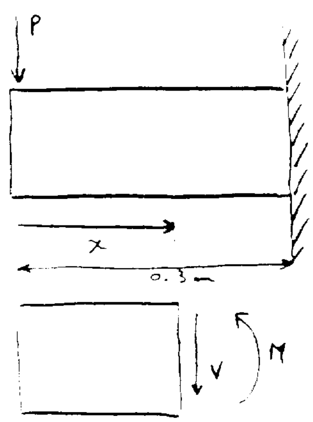
FIND SHEAR STRESS AT LOCATION (A) = τ_{MAX}



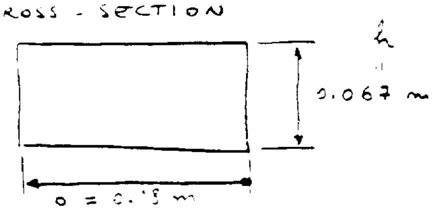
FEMALE CONNECTOR

MALE CONNECTOR

THE MALE CONNECTOR CAN BE SIMPLIFY AS :



CROSS - SECTION



V = SHEAR FORCE

M = MOMENT

P = WEIGHT CARRY BY ONE PAIR OF WHEELS

TOTAL WEIGHT OF VEHICLE $\simeq \dfrac{5800 \text{ kg} \times 9.81}{6} = 9483$ N

$\therefore \quad P = \dfrac{9483.0}{4} = 2371$ N

$V = -P$

$M_{max} = -P x = 2371 \times 0.3 \text{ m} = 711.2 \text{ N.m}$

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OF POOR QUALITY

$$\sigma_{MAX} = \frac{M_{MAX}}{\frac{b h^2}{6}} = \frac{6 \times (711.2)}{0.18 \, (0.067)^2}$$

$$= 5.3 \times 10^6 \text{ Pa.}$$

σ_{MAX} IS BELOW THE BENDING STRENGHT

∴ THE JOINT WILL NOT FAIL UNDER THE LOAD.

$$\tau_{MAX} = \frac{3V}{2bh} = \frac{3}{2}\,\frac{V}{bh}$$

$$= \frac{3}{2}\,\frac{(2371 \text{ N})}{(0.18)(0.067 \text{ m})}$$

$$= 3.0 \times 10^5 \text{ Pa}$$

τ_{MAX} < HALF THE ULTIMATE STRENGTH

∴ THE JOINT WILL NOT FAIL UNDER SHEAR FORCES WHEN LOADED.

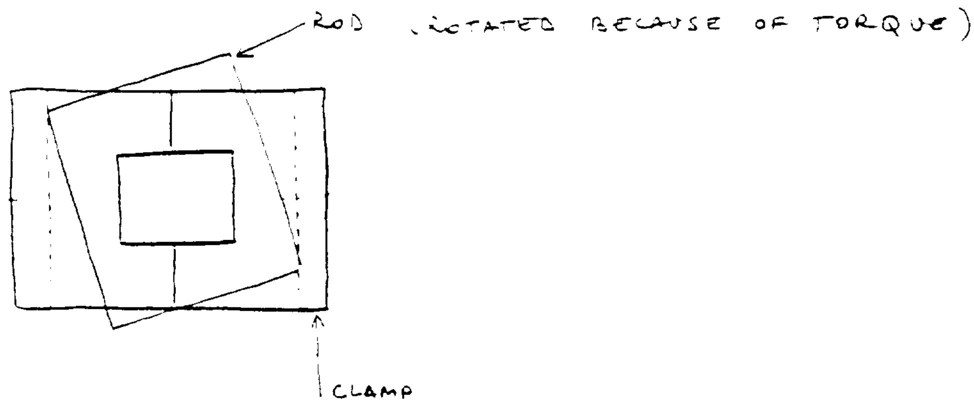
b. MOMENT REQUIRED AT THE ACTUATOR :

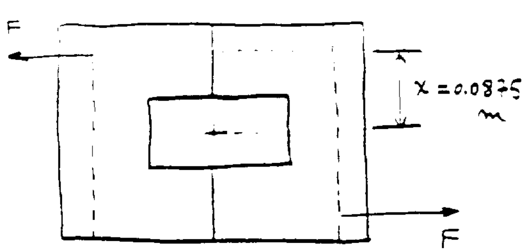
IF A TRACK IS NOT PLACED ON AN EVEN SURFACE (ABOUT $\theta = 10°$ IRREGULARITY), THE WEIGHT OF THE TRACK WILL CREATE A MOMENT AT THE JOINT. THIS MOMENT WILL FORCE

THE ROD (MALE CONNECTOR) ONTO THE CLAMP (FEMALE CONNECTOR) AND WILL TEND TO OPEN THE CLAMP. THEREFORE, THE MOMENT AT THE ACTUATOR MUST BE HIGHER THAN THE MOMENT CREATED BY THE TRACK.

MASS OF ONE TRACK $\Rightarrow M_{ASS} = 112$ KG.

MOMENT $\Rightarrow M = \dfrac{112 \times 9.81}{6} \left(\dfrac{1.2}{2} \right) = 110.3$ N.m





$$2F = \frac{M}{x} = \frac{110.3 \text{ N.m}}{0.0875 \text{ m}}$$

$$F = 630.3 \text{ N}$$

FOR UNEVEN SURFACE OR 10°, THE COUPLING ACTUATOR NEED TO EXERT A FORCE HIGHER THAN 630.3 N.

IF θ IS SMALLER, THE CLAMPING FORCE WILL DECREASE.

ANOTHER WAY TO REDUCE THE CLAMPING FORCE AT THE ACTUATOR WILL BE TO LEAVE A GAP BETWEEN THE ROD AND CLAMP.

APPENDIX D

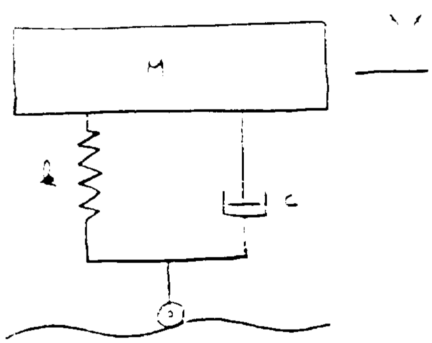
VIBRATION ANALYSIS OF THE SUSPENSION SYSTEM

APPENDIX D

VIBRATION ANALYSIS FOR SUSPENSION SYSTEM

CALCULATION OF DAMPING COEFFICIENT

DUE TO THE UNEVENESS OF TRACK A FORCED VIBRATION OCCURS ON THE VEHICLE. THE SUSPENSION SYSTEM AND THE MOTION OF VEHICLE CAN BE SIMPLIFIED AS FOLLOWS



A. IN THIS CASE THE TRACK GENERATES AN HARMONIC MOTION (ASSUMPTION).

$$y(x) = A \sin \frac{2\pi x}{L}$$

THE DIFFERENTIAL EQUATION OF MOTION HAS THE FORM :

$$M\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0$$

$$\Rightarrow \quad \ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = 2\zeta\omega_n\dot{y} + \omega_n^2 y$$

WHERE ζ = DAMPING RATIO = $\dfrac{c}{2M\omega_n}$

ω_n = NATURAL FREQUENCY = $\sqrt{\dfrac{k}{M}}$

k = SPRING CONSTANT

c = VISCOUS DAMPING COEFFICIENT

D2

THE RESPONSE OF THE SYSTEM IS :

$$x = \frac{A\left[1 + (2\zeta\, \omega/\omega_n)^2\right]^{1/2}}{\left[(1-(\omega/\omega_n)^2)^2 + (2\zeta\,\omega/\omega_n)^2\right]^{1/2}} \sin(\omega t + \alpha - \phi)$$

WHERE $\omega = \dfrac{2\pi V}{L}$

$$\alpha = \tan^{-1} \frac{-\pi / \zeta}{\omega_n L} \quad \text{AND} \quad \phi = \tan^{-1} \frac{2\zeta(\omega/\omega_n)}{1-(\omega/\omega_n)^2}$$

WE NEED TO FIND THE DAMPING RATIO.

WE ASSUME AN UNDERDAMPED SYSTEM

$\therefore \zeta < 1$

FOR $\omega/\omega_n = 1$ $\qquad x = X \sin(\omega t + \alpha - \phi)$

AND $$X = A\left[\frac{1+4\zeta^2}{4\zeta^2}\right]^{1/2}$$

IF WE ASSUME THE AMPLITUDE OF THE FORCED VIBRATION TO BE $A = 0.015$ m DUE TO IRREGULARITIES OF THE UPPER SURFACE OF LESS THAN 5°, THE DAMPING RATIO IS $\simeq 0.57$ FOR A LOW AMPLITUDE OF VIBRATION OF $X = 0.02$ m

X	ζ
0.02	0.57
0.03	0.30
0.04	0.20
0.05	0.16

$$\therefore \boxed{\zeta = 0.57}$$

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ASSUME MASS OF VEHICLE $M = 5800$ Kg

AND SPRING CONSTANT $k = 38.0$ KN/m

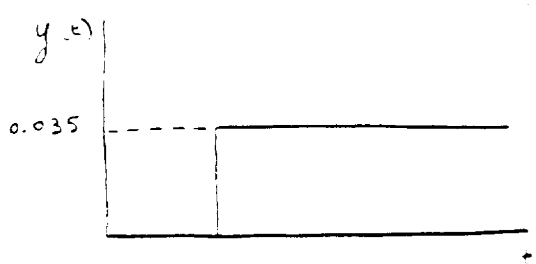
$$\omega_m = \sqrt{\frac{k}{M}} = \sqrt{\frac{38.0 \times 10^3}{5800}} = 2.5 \text{ rad/s}$$

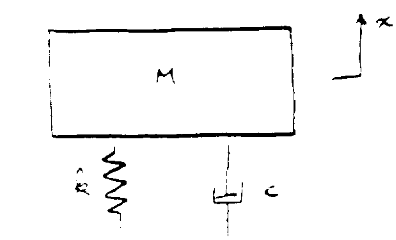
$$\therefore \quad c = 2 M \omega_m \zeta = 2\left[5800 \times 2.5 \times 0.57\right]$$

$$\boxed{c = 16.5 \ \text{N} \cdot \text{s/m}}$$

2. ASSUME WE HAVE A STEP FUNCTION : (SIMPLIFIED MODEL)

$$y(t) = \begin{cases} 0 & \text{for } t < 0 \\ 1 & \text{FOR } t > 0 \end{cases}$$





THE STEP RESPONSE IS :

$$x_1(t) = \frac{1}{k}\left[1 - e^{-\zeta \omega_m t}\left(\cos \omega_d t + \frac{\zeta \omega_m}{\omega_d} \sin \omega_d t\right)\right] \times 0.035$$

D4

THE PLOT OF $x(t)$ VERSUS t IS: (APPROXIMATE)

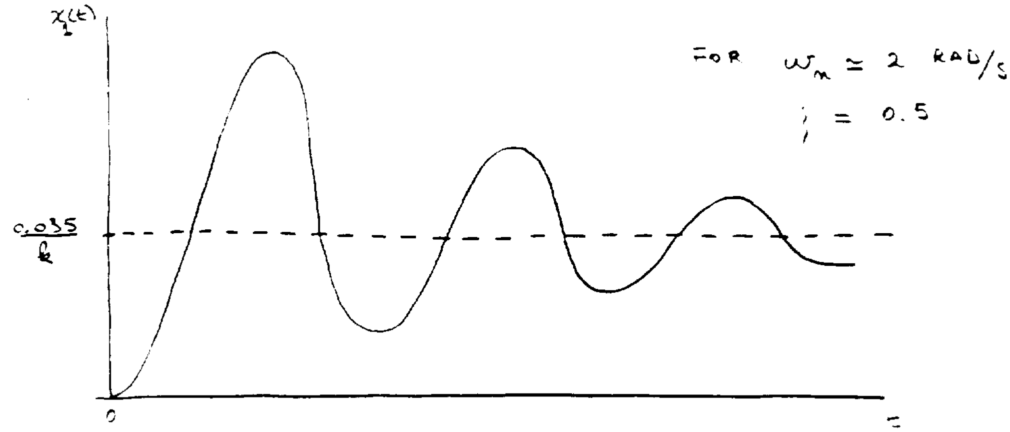
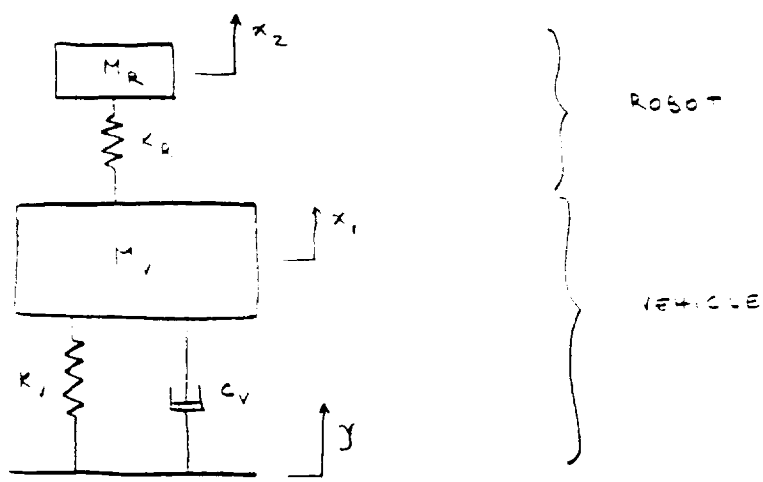


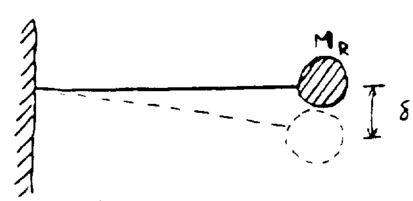
Fig. 1

3. ASSUME A STEP FUNCTION WITH EXPANDED MODEL (VEHICLE + ROBOT ARM)

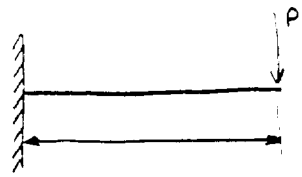
MODEL



THE ROBOT IS MODELED AS ⇒ AND UNDERGOES A DEFLECTION δ.



THE STIFFNESS OF THE ROBOT IS



$$K_R = \frac{P}{\delta}$$

WHERE $$\delta = \frac{PL^3}{3EI}$$

$$K_R = \frac{3EI}{L^3}$$

$E = 114 \times 10^9$ Pa

$L = 1.5$ m

$I = \frac{bh^3}{12}$

EQUATIONS OF MOTIONS ARE :

$$M_v \ddot{x}_1 + c_v \dot{x}_1 + (k_v + k_R)\, x_1 - k_R x_2 = k_v y_0 + c_v \dot{y}_0$$

$$M_R \ddot{x}_2 + k_R x_2 - k_R x_1 = 0$$

$$\begin{bmatrix} M_v & 0 \\ 0 & M_R \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_v & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_v + k_R & -k_R \\ -k_R & k_R \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$= \begin{bmatrix} 0.035\, k_v \\ 0 \end{bmatrix}$$

THE RESPONSE OF DAMPED SYSTEM IS :

$$\{x(t)\} = e^{[A]t} \{x(0)\} + \int_0^t e^{[A]t} [B] \{X(t)\}\, dt$$

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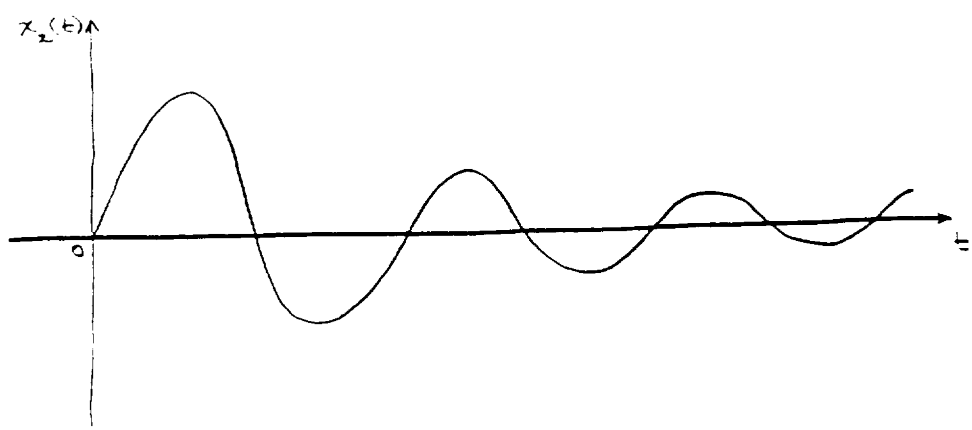
WHERE $$[A] = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{K_V + K_R}{M_V} & \frac{K_R}{M_V} & -\frac{C_V}{M_V} & 0 \\ \frac{K_R}{M_R} & -\frac{K_R}{M_R} & 0 & 0 \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1/M_V & 0 \\ 0 & 0 & 0 & 1/M_R \end{bmatrix}$$

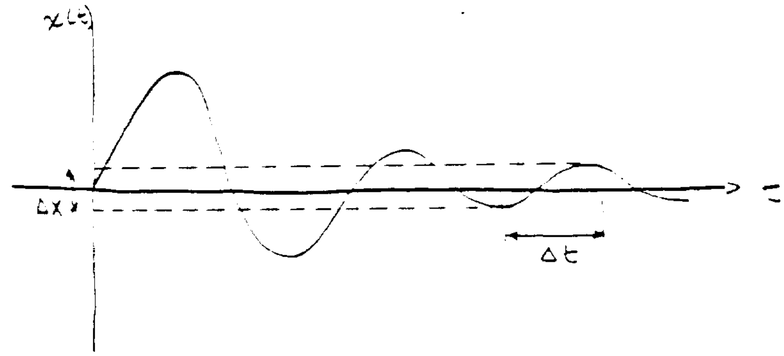
AND $$\{X\} = \begin{Bmatrix} 0 \\ 0 \\ 0.035\ K_V \\ 0 \end{Bmatrix}$$

THIS RESPONSE REQUIRES THE USE OF COMPUTATIONAL TECHNIQUES. BUT

THE ANTICIPATED RESPONSE IS :



AFTER INITIAL EXCITATION, WE NEED TO LET THE VEHICLE (SYSTEM) DAMP OUT BEFORE ALLOWING THE ROBOT END EFFECTOR TO PICK UP THE TRACK, OR ALLOWING A TIME RANGE DURING WHICH THE ROBOT CAN PICK UP THE TRACK (SEE FIG.)



FOR THIS TIME RANGE (Δt), the SYSTEM WILL ALLOW MINIMUM DISPLACEMENT RANGE $\Delta x(t)$. WHEN WITHIN THIS RANGE, THE ROBOT WILL CORRECTLY PICK UP THE TRACK.

CONCLUSION :

SINCE THE ROBOT WILL POSITION THE TRACK AT A TIME INTERVAL OF 0.72 SEC, WE WILL NEED A SYSTEM REACHING EQUILIBRIUM AS FAST AS POSSIBLE. THIS MEANS THAT THE DAMPING RATIO NEEDS TO BE $\boxed{\zeta = 1.0}$

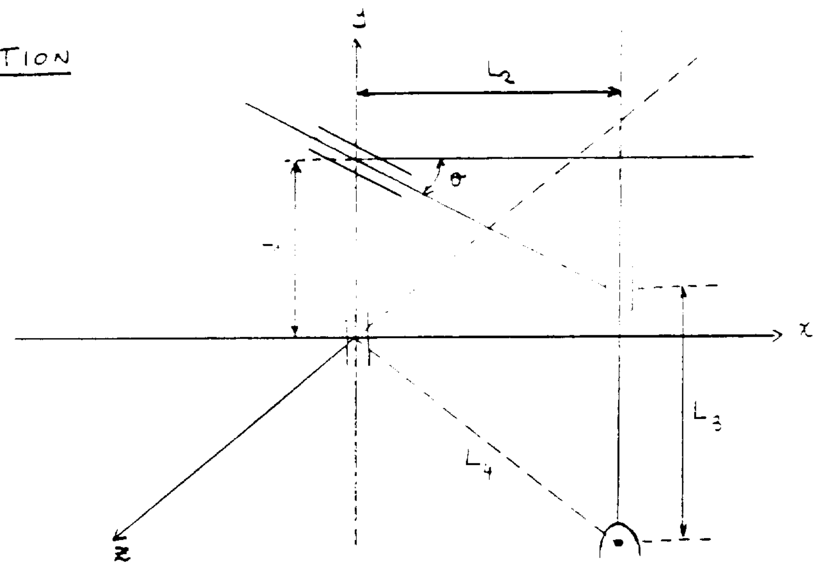
APPENDIX E

KINEMATICS ANALYSIS OF THE ROBOTIC ARM

APPENDIX E

KINEMATIC ANALYSIS OF ROBOTIC ARM

ROBOT CONFIGURATION



A. POSITION OF END EFFECTOR :

$$L_4^2 = L_{4x}^2 + L_{4y}^2 + L_{4z}^2$$

$$L_4^2 = L_2^2 + (L_1 - L_3)^2 + \left(\frac{L_2}{\cos\theta}\right)^2 \qquad (1)$$

$$L_4^2 = \left[L_2^2\left(1 + \frac{L_2}{\cos^2\theta}\right)\right] + \left[L_1 - L_3\right]^2$$

B. VELOCITY OF END-EFFECTOR

DIFFERENTIATE (1) WITH RESPECT TO TIME YIELDS THE VELOCITY OF THE LINKS

$$2L_3\frac{dL_3}{dt} - 2L_3\frac{dL_1}{dt} - 2L_1\frac{dL_3}{dt} - 2L_1\frac{dL_1}{dt}$$

$$- 2L_4\frac{dL_4}{dt} + 2L_2\left(1+\frac{1}{\cos^2\theta}\right)\frac{dL_2}{dt} + L_2^2\left(\frac{2\cos\theta\sin\theta}{(\cos^2\theta)^2}\right)\frac{d\theta}{dt}$$

$$= 0$$

$$2(L_3-L_1)\frac{dL_3}{dt} + 2(L_1-L_3)\frac{dL_1}{dt} - 2L_4\frac{dL_4}{dt}$$

$$+ 2L_2\left(1+\frac{1}{\cos^2\theta}\right)\frac{dL_2}{dt} + L_2^2\left(\frac{2\cos\theta\sin\theta}{(\cos^2\theta)^2}\right)\frac{d\theta}{dt} = 0 \qquad (2)$$

WHERE $\frac{dL_i}{dt}$ = LINEAR VELOCITY OF LINK i

$\frac{d\theta}{dt}$ = ANGULAR VELOCITY

C. ACCELERATION OF END EFFECTOR

DIFFERENTIATE (2) WITH RESPECT TO TIME YIELDS THE ACCELERATION OF LINKS.

THE FINAL EQUATION IS

$$(L_3-L_1)\frac{d^2L_3}{dt^2} + \left(\frac{dL_3}{dt} - \frac{dL_1}{dt}\right)^2 + (L_1-L_3)\frac{d^2L_1}{dt^2}$$

$$- L_4\frac{d^2L_4}{dt^2} - \left(\frac{dL_4}{dt}\right)^2 + \left(1+\frac{1}{\cos^2\theta}\right)\left[L_2\frac{d^2L_2}{dt^2} + \left(\frac{dL_2}{dt}\right)^2\right]$$

$$+ \left[\frac{L_2 \sin\theta}{\cos^3\theta} \right] \left(4 \frac{d\theta}{dt} \frac{dL_2}{dt} + L_2 \frac{d^2\theta}{dt^2} \right)$$

$$- L_2^2 \left[1 + \frac{8}{\cos^2\theta} \right] \left(\frac{d\theta}{dt} \right)^2 = 0 \qquad (3)$$

THE KINEMATICS OF THE ROBOTIC ARM IS GOVERN BY EQUATION (1), (2), (3).

IF WE ASSUME T = 0.72 SEC FOR THE ROBOT TO PICK UP THE TRACK

I. BACK ROBOTIC ARM

$L_1 = 1$ m IN 0.72 SEC

$L_2 = 0.23$ m IN 0.72 SEC.

$\theta = 0.928$ RADIAN IN 0.72 SEC.

$L_3 = 5$ m IN 0.72 SEC.

$\dot{L}_1 = 1.39$ m/s

$\dot{L}_2 = 0.32$ m/s

$\dot{L}_3 = 6.94$ m/s

$\dot{\theta} = 1.29$ RAD/s

$\ddot{L}_1 = \dfrac{\dot{L}_1^2}{2\Delta L_1} = 0.97$ m/s²

$\ddot{L}_2 = 0.22$ m/s²

$\ddot{L}_3 = 4.82$ m/s²

$\ddot{\theta} = \dfrac{\dot{\theta}^2}{2\Delta\theta} = 0.90$ rad/s²

POSITION :

$L_1 = 0.5$ m

$L_2 = 0.115$ m

$L_3 = 2.5$ m

$\theta = 0.464$ RADIAN

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E4

FIND L_4 :

$$L_4 = \left[L_2^2 \left(1 + \frac{1}{\cos^2\theta}\right)\right] + (L_1 - L_3)^2$$

$$= \left[(0.115)^2 \left(1 + \frac{1}{\cos^2(0.464)}\right)\right] + (0.5 - 2.5)^2$$

$$= 4.03 \text{ m}$$

<u>VELOCITY</u>

$\dot{L}_1 = 1.39$ m/s $\quad \dot{L}_3 = 6.24$ m/s

$\dot{L}_2 = 0.32$ m/s $\quad \dot{\theta} = 1.29$ rad/s

$$\dot{L}_4 = \left[(L_3 - L_1)\dot{L}_3 + (L_1 - L_3)\dot{L}_1 + L_2\left(1 + \frac{1}{\cos^2\theta}\right)\dot{L}_2 + L_2^2\left(\frac{\sin\theta}{\cos^2\theta}\right)\dot{\theta}\right] / L_4$$

$$\boxed{\dot{L}_4 = 2.28 \text{ m/s}}$$

<u>ACCELERATION</u>

$$\ddot{L}_4 = \left\{ (L_3 - L_1)\ddot{L}_3 - (L_1 - L_3)\ddot{L}_1 + (\dot{L}_3 - \dot{L}_1)^2 - \dot{L}_4^2 + \left(\left(1 + \frac{1}{\cos^2\theta}\right)\left(L_2\ddot{L}_2 + \dot{L}_2^2\right)\right) + \left[\frac{L_2 \sin\theta}{\cos\theta}\right] \times \left(4\dot{\theta}\dot{L}_2 + L_2\ddot{\theta}\right) + L_2^2\left[1 + \frac{\ell}{\cos^2\theta}\right]\dot{\theta}^2\right] / L_4$$

$$\boxed{\ddot{L}_4 = 7.8 \text{ m/s}^2}$$

E5

II. FRONT ROBOTIC ARM :

L_1 MOVES AT 1 m IN 0.72 SEC.

L_2 " " 0.8 m " "

θ " " 1.18 RAD IN 0.72 SEC

L_3 " " 5 m IN 0.72 SEC

$\dot{L}_1 = 1.39$ m/s

$\dot{L}_2 = 1.11$ m/s

$\dot{\theta} = 1.63$ RAD/s

$\dot{L}_3 = 6.94$ m/s

$$\ddot{L}_1 = \frac{\dot{L}_1^2}{2\Delta L_1} = 0.97 \text{ m/s}^2$$

$\ddot{L}_2 = 0.77$ m/s²

$\ddot{\theta} = 1$ RAD/s²

$\ddot{L}_3 = 4.82$ m/s²

POSITION :

$L_1 = 0.5$ m

$L_2 = 0.4$ m

$L_3 = 2.5$ m

$\theta = 0.59$ RAD

FIND L_4 :

$$L_4 = \left[L_2^2 \left(1 + \frac{1}{\cos^2\theta} \right) \right] + (L_1 - L_3)^2$$

$$= \left[(0.4)^2 \left(1 + \frac{1}{\cos^2 33.63} \right) \right] + (0.5 - 2.5)^2$$

$$\boxed{L_4 = 4.39 \text{ m}}$$

VELOCITY :

$$\dot{L}_4 = \left[(L_3 - L_1)\dot{L}_3 + (L_1 - L_3)\dot{L}_1 + L_2 \left(1 + \frac{1}{\cos^2\theta} \right) \dot{L}_2 + L_2^2 \left(\frac{\sin\theta}{\cos^3\theta} \right) \dot{\theta} \right] \Big/ L_4$$

$$\boxed{\dot{L}_4 = 2.83 \ m/s}$$

ACCELERATION:

$$\ddot{L}_4 = \Big[(L_3 - L_1)\ddot{L}_3 + (L_1 - L_3)\ddot{L}_1 + (\dot{L}_3 - \dot{L}_1)^2 - \dot{L}_4^2$$

$$+ \left[\left(1 + \frac{1}{\cos^2\theta}\right)\left(L_2 \ddot{L}_2 + \dot{L}_2^2\right)\right] - \left[\frac{L_2 \sin\theta}{\cos^3\theta}\right] \times$$

$$\left[4\dot{\theta}\dot{L}_2 + L_2\ddot{\theta}\right] + L_2^2\left[1 + \frac{3}{\cos^2\theta}\right]\dot{\theta}^2\Big] \Big/ L_4$$

$$\boxed{\ddot{L}_4 = 9.70 \ m/s^2}$$

APPENDIX F

MATERIALS PROPERTIES

TABLE F.1: TITANIUM AND ALUMINUM PROPERTIES

Mechanical Properties of Some Wrought Titanium Alloys

		Tensile Strength						
		Ultimate, S_u		Yield, S_y		Elongation in 2 in.	Charpy Impact Strength	
Alloy	Designation	ksi	MPa	ksi	MPa	(%)	ft-lb	J
Comml. pure alpha Ti	Ti-35A	35	241	25	172	24	11–40	15–54
Comml. pure alpha Ti	Ti-50A	50	345	40	276	20	11–40	15–54
Comml. pure alpha Ti	Ti-65A	65	448	55	379	18	11–40	15–54
Alpha alloy	Ti-0.2Pd	50	345	40	276	20	—	—
Alpha-beta alloy	Ti-6Al-4V	120–160*	896–1103*	120–150*	827–1034*	10–7	10–20	14–27
Beta alloy	Ti-3Al-13V-11Cr	135–188*	931–1296*	130–175*	896–1207*	16–6	5–15	7–20

*Depending on heat treatment.

Note: Values tabulated are approximate median expectations.

Source: Machine Design, 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio, Vol. 53, No. 6 (March 19, 1981).

Mechanical Properties, Characteristics, and Typical Uses of Some Wrought Aluminum Alloys

		Tensile Strength												
		Ultimate, S_u		Yield, S_y		Elong. in 2 in.								
Alloy	Hard., H_B	ksi	MPa	ksi	MPa	(%)	Corr. Resist.	Cold Work	Machine	Braze	Gas Weld	Arc Weld	Resist. Weld	Typical Uses
1100-0	23	13	90	5	34	45	A	A	E	A	A	A	B	Spinnings, drawn shapes, heat exchangers, cooking utensils, tanks
-H14	32	18	125	17	115	20	A	A	D	A	A	A	A	
-H18	44	24	165	22	150	15	A	B	D	A	A	A	A	
2011-T3	95	55	380	43	295	15	D	C	A	D	D	D	D	Screw machine products
-T8	100	59	405	45	310	15	D	D	A	D	D	D	D	
2014-0	45	27	185	14	97	18	—	—	D	D	D	D	B	Heavy duty forgings, aircraft structures and fittings, truck frames
-T4	105	62	425	42	290	20	D	C	B	D	D	B	B	
-T6	135	70	485	60	415	13	D	D	B	D	D	B	B	
2024-0	47	27	185	11	76	22	—	—	D	D	D	D	D	Aircraft structures, truck wheels, screw mach. products
-T4	120	68	470	47	325	19	D	C	B	D	C	B	B	
6061-0	30	18	125	8	55	30	B	A	D	A	A	A	B	Boats, rail cars, pipe, flanges, trailers
-T6	95	45	310	40	275	17	B	C	C	A	A	A	A	
6063-0	25	13	90	7	48	—	A	A	—	A	A	A	A	Furniture tube, doors, windows, pipe, fuel tanks
-T6	73	35	240	31	215	12	A	C	C	A	A	A	A	
7075-0	60	38	230	15	105	16	—	—	D	D	D	C	B	Aircraft structures and skins, ski, railings
-T6	150	83	570	73	505	11	C	D	B	D	D	C	B	

Note: Values are approximate median expectations for sizes about ½ in. H_B values were obtained from 500-kg load and 10-mm ball. Letters A, B, C, D indicate relative ratings in decreasing order of merit.

Source: ASM Metals Reference Book, American Society for Metals, Metals Park, Ohio, 1981.

TABLE F.2: CARBON FIBER EPOXY (COMPOSITE)

PRINCIPAL PROPERTIES

COMMERCIAL NAME	E 21718 x 60	E 21718 x 61	E 21718 x 65
MANUFACTURER/SUPPLIER	Fiberite	Fiberite	Fiberite
GENERIC TYPE	Epoxy (TS)	Epoxy (TS)	Epoxy (TS)
FILLERS/COPOLYMERS	Carbon Fiber	Carbon Fiber	Carbon Fiber
SPECIAL FEATURES	Versatile Structural long fibers	Versatile Structural long fibers High strength carbon fiber	Versatile Structural long fibers High modulus fiber
APPLICATIONS/USES	Structural grade	Structural grade	Structural grade
CONSTRUCTION/CURE PARAMETERS	0.5" chop st carbon (1/4", 3/4", 1" &2" available)	0.5" chop HS carbon (1/4", 3/4", 1" &2" available)	0.5" chop HM carbon (1/4", 3/4", 1" &2" available)
SPECIFICATIONS			

PROPERTIES	English	Metric	E 21718 x 60		E 21718 x 61		E 21718 x 65	
Processing Method			Compression molding		Compression molding		Compression molding	
Processing Temp	°F	°C	315°F	157°C	315°F	157°C	315°F	157°C
Density	lb/ft³	g/cm³	94.3	1.51	94.3	1.51	94.3	1.51
Linear Mold Shrinkage	in/in		0		0		6.00x10⁻³	
Water Absorption, 24 hours, %			0.20		0.20		0.20	
MECHANICAL PROPERTIES								
Tensile Strength, Break	psi	kg/cm²	3.00x10⁴	2.11x10³	3.20x10⁴	2.25x10³	1.80x10⁴	1.27x10³
Tensile Modulus	psi	kg/cm²						
Elongation %, Break								
Flexural Strength, Break	psi	kg/cm²	5.40x10⁴	3.80x10³	5.80x10⁴	4.08x10³	5.30x10⁴	3.73x10³
Flexural Modulus	psi	kg/cm²	7.20x10⁶	5.06x10⁵	8.20x10⁶	5.76x10⁵	1.18x10⁷	8.30x10⁵
Izod, Notched, @ RT	ft lb/in	kg cm/cm	20.0	109	25.0	136	15.0	81.6
Izod, Unnotched, @ RT	ft lb/in	kg cm/cm						
Compressive Strength	psi	kg/cm²	3.60x10⁴	2.53x10³	4.40x10⁴	3.09x10³	3.10x10⁴	2.18x10³
Hardness	Value (Test)		M115 (Rockwell)		M115 (Rockwell)		M115 (Rockwell)	
THERMAL PROPERTIES								
Deflection Temp, @264 psi	°F	°C	482°F	250°C	482°F	250°C	482°F	250°C
Deflection Temp, @66 psi	°F	°C						
Linear Thermal Expansion	in/in °F	cm/cm °C						
Thermal Cond	BTU in/hr ft² °F	cal cm/sec cm² °C						

End date Aug 16, 1990